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RESEARCH ARTICLE

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Carbon Cycle Models Quantify for a Green and Low-Carbon Economy

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Abstract: CO_2 emissions from the combustion of fossil fuels represent the largest anthropogenic disruption of the natural global carbon cycle and lead to an undesirable increase in atmospheric CO_2 levels. The so-called "carbon-neutral" renewable energy source biomass appears to be a promising replacement for fossil fuels. The "Combined Energy and Biosphere Model" (CEBM) was developed as a method for calculating the atmospheric CO_2 content after intensive use of biomass. It includes (i) a biosphere part computing the annual cycle of carbon in the biosphere on 2,433 grid elements covering the continents' plant mass and soil and (ii) an energy economic part for calculating the fossil CO_2 emissions of 119 countries. As the history of understanding the carbon cycle (including quantification of plant growth and decay by formulae, inclusion of deforestation, fossil fuel use, and the fertilizer effect) shows, such a global carbon cycle model (as the CEBM) provides the needed methodology to assess the net effects of large-scale biomass energy use on the plant's atmosphere. Results show that biomass (in a systemic view) is "only half as carbon neutral" as previously thought, even on a principal level. The conclusions indicate that (even if biomass is a valuable mitigation strategy) its global potential is limited. When interpreting CEBM scenarios, as a very first priority, reducing the current annual increase in energy demand is most highly needed for preserving climate.

Keywords: global change, climate change, biomass energy, carbon cycle, global carbon model, CO_2 emission scenarios, Combined Energy and Biosphere Model

The recent "European Green Deal" [1] calls for quantification of the positive effect of various climate protection strategies on the CO_2 content in the atmosphere [2]. The presented models offer support to achieve this goal. Especially because a recent publication [3] received interest [4–8], the present article undertakes to dwell more into modeling details on the global carbon cycle.

This article contributes to answering the question: what functional features must global models have in order to solve the question "is biomass energy carbon neutral?".

1. Introduction

One of the concrete options for a green and low-carbon economy is biomass fuels which mostly offer their readiness to be implemented instantly [9–11]. However, their overall impact and net effect on the atmospheric CO_2 concentration remain to be evaluated, as recent literature emphasizes [12–16], especially using a dynamic model [17–20]. For this target, the author undertook a project named "Influence of increased energy use of biomass on the CO_2 concentration in the atmosphere" based on the idea that a reduction in anthropogenic, energy-related CO_2 emissions can be achieved by using biomass as fuel (e.g., wood: [21]) instead of fossil fuels (e.g., coal, oil, and gas), but must be further assessed quantitatively [22–27], best by a geographically resolved model [28–30]. The general assumption that the renewable raw material biomass absorbs the same amount of CO_2 from the atmosphere during its growth that it releases when it is burned is voiced since long (e.g., since [31–37], even by proponents of biomass energy [38, 39] and led to the term "biomass is a carbon-neutral energy source" [40–42].

Because the effects on the carbon cycle associated with the increased global use of biomass as a fuel are diverse and difficult [43–46] (as shown by models of simple or medium degrees of complexity [47–49]) this study was designed as a modeling exercise with the aim of examining the changes in the carbon cycle in geographic detail.

The results of this modeling exercise relate, on the one hand, to the global *potential for biomass fuels and, on the* other hand, to the resulting *mitigation of the increase in* CO_2 *in the atmosphere* as a result of different scenarios [50–55] and thus to providing an answer to the question of carbon neutrality of biomass energy strategies.

For these targets, the author constructed the "Combined Energy and Biosphere Model" (CEBM), based on an earlier carbon cycle model Osnabrück Biosphere Model (OBM), encountered at his workplace International Institute for Systems Analysis (IIASA) [56, 57] that (i) later inspired the "Global Change Data Base" [58, 59] for scenario generation [51] and (ii) also was integrated into the EU project [60].

There exist also other modeling approaches such as for the "Biosphere 2" project [61] which, however, envisage the question if humans can survive in segregated volumes offering oxygen for breathing as a result of plant activity.

Overall, the present article contributes to clarifying which dynamic properties, which functions, which parameters and variables, which flows and pools of carbon a global model must include to be able to reasonably answer the question: to which

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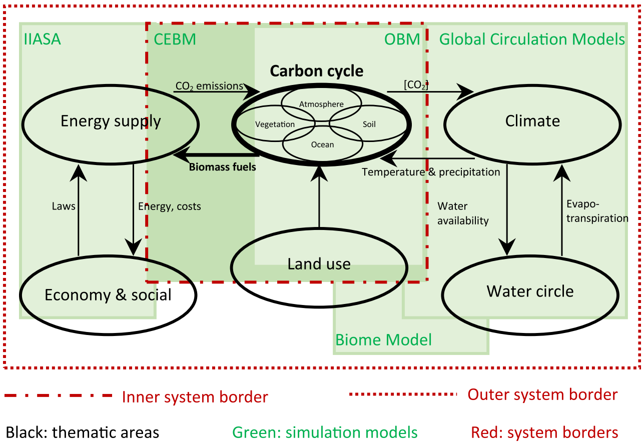
degree are biomass fuels carbon neutral, and how is the dynamic equilibrium of the global carbon cycle altered in the short-term and long-term perspective? Which portion of the global energy demand can biomass fuels cover under which circumstances and in which socio-techno-economic scenarios? Does biomass fulfill the existing hopes of being perfectly carbon neutral – or which limitations are there under which circumstances and how can these be (politically, strategically) controlled?

1.1. Thematic areas described by this model

The core topic of the CEBM focuses on the area of atmospheric CO_2 concentration and thus the *carbon cycle* in atmosphere, biosphere, and ocean. Any additional effects of a biomass-centered global energy system (e.g., economy, climate, ecology, etc.,) were left out from this C-cycle model (see Figure 1 on model borders).

Figure 1
Thematic areas described by the CEBM and adjacent models



Desired additional effects of the energetic use of biomass include the following: improvement of the income structure of the agricultural population, concentration of value creation (in the area of energy sources) domestically, sensible use of surplus agricultural land, partial reduction of transport routes for energy sources, crisis-proof energy supply through decreasing dependence on global politics sensitive zones, realizing the idea of a circular economy and much more.

Possible *undesirable consequences* of intensive biomass use could be necessary costly technological changes to combustion plants, more or less complex conversion processes from primary energy to secondary energy, increased need for manual labor during plant cultivation and harvest, possible withdrawal of nutrients from the soil, severe land use conflicts with food production and with undisturbed nature reserves, limited biodiversity (reduction in the number of species as a result of monocultures), possible increased need for fertilizers and pesticides, worsened fuel storability due to lower energy density, need for large-scale technological conversion of technical facilities, and other possible effects.

This work on the CEBM had to concentrate on the carbon cycle, and a full quantitative coverage of other thematic areas was not possible, only the C cycle was modeled (except detailed driving energy scenarios). Likewise, the conversion processes of the biomass present as raw material into secondary energy sources, such as liquid or gaseous fuels, were not examined, but only the energy content of the solid fuel biomass was used. Pricing on the energy market was also not quantitatively included. Already, the precise computation of the core topic "carbon cycle" alone is able to produce valid and reliable results.

This work therefore perceives reality through a "carbon lens," meaning that only amounts of C are perceived but (during quantitative modeling) not the amounts of other matter such as oxygen, water, or minerals.

1.2. The research problem and hypotheses

In a nutshell, the research question reads: "to what extent is biomass energy carbon neutral?"

The hypotheses made include the conviction that a quantitative, geo-referenced carbon cycle model is a valid tool to answer this research question and that a scenario technique (while assuming cases of maximum exploitation of worldwide biomass energy potentials) will inform about the overall net effect of biomass energy in this extreme case of exploitation.

The purpose of this entire research lies in finding consultancy for policy making on national and transnational levels (such as the EU) in order to resolve the question: "which role should biomass energy play in a sustainable future, and at what principal level of biospheric risks?"

For an introductory literature review into the question of carbon neutrality, see [3].

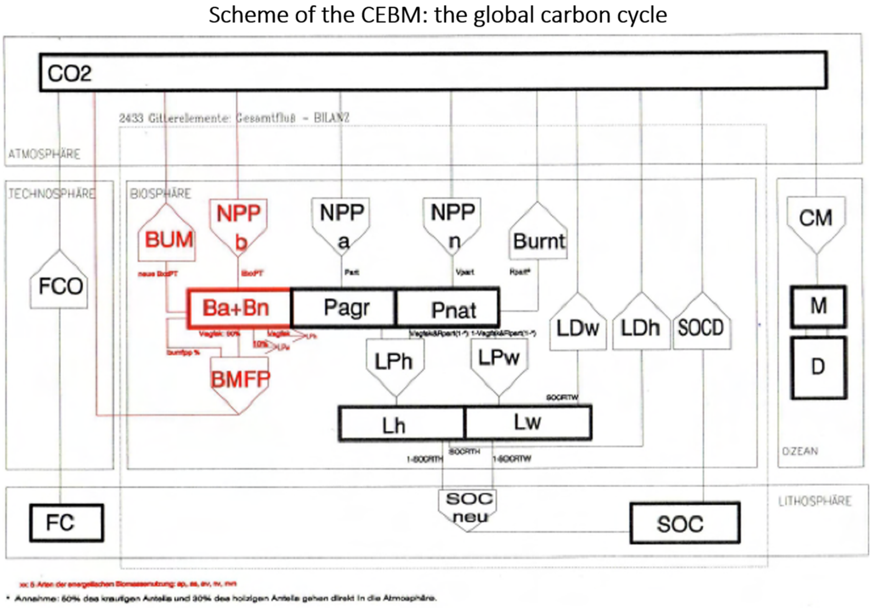
1.3. A short history of carbon cycle models

One of the earliest carbon cycle models has been developed at the University of Osnabrück in Germany since around 1980 [62–67]. Basically, the OBM is organized in such a way that each grid element is divided into areas allocated to natural ("n") and agricultural ("a") vegetation. As the CEBM expands, the options for area allocation from two to three, namely including biomass growth areas ("b"), areas for the various methods of biomass fuel production, will be added in a way that all areas complement each other to 100%. The link between the C reservoirs and C flows can be seen in Figure 2 [68], especially for the C flows net primary productivity (NPP) and standing phytomass.

The OBM's and CEBM's view is that the prehistoric state of the carbon cycle, undisturbed by humans, is understood as the result of the steady state of the carbon fluxes calculated annually for the entire planet. For this reason, a so-called "preliminary run" must be carried out with the model over several thousand (theoretical) model years, which calculates the size of the carbon reservoirs in this almost stable steady state. This transient process, which only includes natural processes, was carried out at the beginning of the project. The result of these preliminary model runs is the so-called starting values for the biosphere reservoirs from 1860, the year defined as the beginning of industrialization and thus of fossil emissions and deforestation emissions. From this point on (1860), so-called "zero runs" were carried out to check the computational correctness of the model: both the fossil and the clearing emissions were artificially set to zero, which, as expected, caused the atmospheric CO_2 concentration to remain at the level from 1860 (= 287 ppm or parts per million).

Furthermore, the **Frankfurt Biosphere Model** (FBM) was developed by the working group of Prof. Gundolf H. Kohlmaier at the Institute for Physical and Theoretical Chemistry at the J.W. Goethe University in Frankfurt [69–72]. This global three-compartment model for the carbon cycle includes deforestation and other land use changes with their influence on the plant

Figure 2
The structure of the global carbon reservoirs and flows in the CEBM (Ahamer, 2019: 304)



cover/soil system. As in the OBM, the CO_2 fertilization effect is included as well as global temperature warming due to increasing atmospheric CO_2 concentrations, impacting on the growth functions. Soil carbon was recognized in the cited work as a large reservoir for potential additional CO_2 emissions as a result of global warming. (7 to 39% of global soil carbon can be emitted as a result of a 2°C increase in temperature).

One characteristic of the FBM is its way of thinking in feedback loops (e.g., with reference to Lovelock's Gaia hypothesis (e.g., in [73, 74]), which seems to correspond to the given complex ecological system. The different time constants for the compartments of plant mass, stand waste/topsoil, and finally "bottom soil humus" are taken into account separately. In the FBM, as in the OBM, it is assumed that the inventory waste production in stationary equilibrium is equal to the NPP.

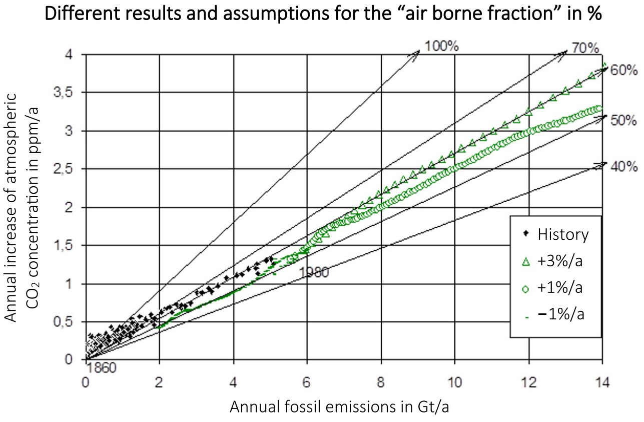
Although the functional relationships for NPP, fertilizer effect, and similar flows appear to be modeled more simply in the FBM than in the OBM [71], the cited documentation provides a detailed discussion of net biospheric emissions over the last century. As expected, the result of the biospheric CO_2 net emission is very sensitive to the assumptions made and the model architecture. These net emissions are the numerically small difference between large C amounts and are therefore strongly influenced by potential sources of error.

The **Münster Climate Model** is a simplified combination of the Hamburg climate model developed in the working group of Prof. Wilfrid Bach with the addition of other models. A detailed description can be found, for example, in Pieler et al. [75], Jain and Bach [76] from the Institute of Geography at the University of Münster, as encouraged by the German Bundestag [77].

The carbon model by Hartmut **Bossel** [78] describes the carbon cycle without geographic differentiation.

In the light of the above, a very simple dimensionless number as a quick assessment measure (in the sense of a rule of thumb for comparing model behavior) can be thought out, namely a constant percentage number called "air-borne fraction." The easiest way to illustrate how a carbon cycle model works is to calculate the share of the emitted carbon remaining in the atmosphere and not being absorbed by biosphere, ocean, or other possible sinks. As expectable, such percentage depends on the level of the atmospheric CO_2 concentration as well as on its rate of change over time (i.e., speed of change). In graphic form, a diagram with the annual CO_2 emissions (= cause) as the horizontal axis and the annual increase in CO_2 emissions (= effect) as the vertical axis allows a quick overview of different models without having to get into the depths of a program listing. This is carried out in Figure 3 [79] in a preliminary form for the CEBM, whereby on the emissions side only fossil emissions are taken into account, but not deforestation emissions, and three scenarios are shown for the future. Each data point corresponds to one model year.

Figure 3
The proportion of CO_2 remaining in the atmosphere according to the CEBM from 1860 onwards for 3 scenarios



1.4. The methodology used in this research

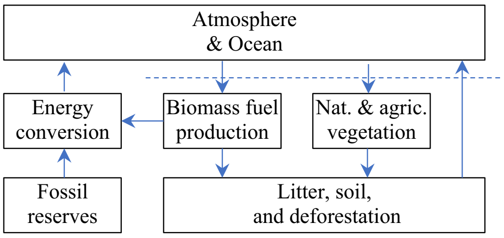
The CEBM, as many other global carbon models described above, computes on the surface of the continents first the fluxes of carbon and second the pools of carbon. By this annual exercise, the global carbon cycle is modeled according to the structure presented in Figure 2.

This methodology is further described in [3, 68, 79], and timelines for each flux or pool illustrate in detail the functioning of this model. Within the ESCOBA project [80, 81], the CEBM and similar global carbon cycle models were included in a benchmarking exercise that yielded comparable results for all contemporary global models [82]. Therefore, no dedicated chapter on "methodology" is repeated here.

2. The CEBM in detail: Fundamental results

Figure 4 [83] shows schematically how the structure of the global carbon cycle is reflected by the CEBM program structure, leading along the path atmosphere → biomass → litter → soil → atmosphere (and partly → ocean), with input from fossil reserves.

Figure 4
The basic program structure of the CEBM in accordance with the carbon cycle



This structure of the CEBM into subprograms corresponds to the linking of the C reservoirs (Figure 4). Due to the law of mass conservation, the contents of the individual C reservoirs (such as litter or soil organic carbon) are calculated mathematically from the so-called balance equation (influx minus outflux = annual increase in the reservoir), i.e., from quite simple formulas that consist of additions and subtractions. Much more complex formulas, however, determine the annual fluxes (or flows) of carbon, because these are functions of local mean temperature and mean rainfall. In terms of visual appearance of formulas, signs for multiplication, division, and exponential functions predominate here.

2.1. Mass ratios within the carbon cycle

As a first step in any modeling exercise, the mutual relations and comparative sizes of the various carbon reservoirs and fluxes should be critically reviewed in order to understand the overall time dynamics of the entire planetary carbon flow system. A useful and in-depth work is that of [84]. In the literature used, there is broad agreement about the numerical values for the carbon content in the individual reservoirs.

Accordingly, the carbon content of the atmosphere amounted to around 720 Gt C in 1990 and that of the standing living plant mass (phytomass) to around 650 Gt C (of which 3 Gt C is present in agricultural plants). The estimated value for the amount of organic carbon contained in the soil humus (above layers) is around 1,550 Gt C, and the pool of so-called litter consisting of dead plant parts is around 72 Gt C. These main carbon stores in the biosphere are connected by an annual cycle of around 45 Gt C/a. This carbon cycle is ultimately powered by energy from the sun. NPP, i.e., effective plant growth, is the difference between gross primary productivity and respiration (plant respiration). It is instructive to keep in mind that approximately one-fifteenth of the carbon deposited as plant matter is in circulation each year and that the carbon stock in the atmosphere and in the plant matter is approximately the same size (1 ppm $CO_2 = 2.11$ Gt C and 1 Gt C = 3.66 Gt CO_2).

Two other important carbon reservoirs associated with the atmosphere are the fossil deposit (probably about 6,600 Gt C) and the ocean (probably 40,000 Gt C), which can physically dissolve CO_2 (depending on its temperature). The extremely large carbon deposit that is found in the carbonate rock of the earth's crust, for example in limestone mountains (around 60 to 100 million Gt C), is not taken into account in this model because the exchange processes with the atmosphere are assumed to be both small and very slow. Another carbon reservoir not taken into account here is the marine biomass, which, although small in size, turns over a considerable amount of CO_2 annually through photosynthesis activity. It can be assumed that the omission of these difficult-to-model processes does not disrupt the final results of the CEBM.

2.2. Description of biospheric carbon flows

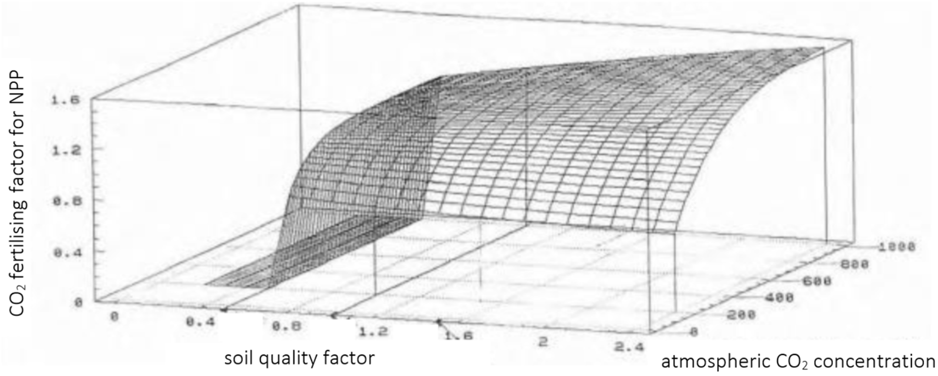
On every single of the 2433 grid elements covering the planet, the so-called net biospheric flux ("balance," dotted line in Figure 4) results from the balance equation for phytomass growth and decay. In addition to fossil CO_2 emissions, this balance forms the second anthropogenic source, namely the biospheric emissions, which also include deforestation emissions.

It is a characteristic of this biosphere model that a stationary state (i.e., an equilibrium of flows in and out) is assumed for the biotopes (with the only exception of "reallocation of areas," see later). This term "stationary state" means that the plants are in balance between growth and natural death, so that no growth processes need to be modeled on the level of a single plant during their multi-year dynamics.

Similar to how the proportions of the different carbon reservoirs were compared above, the proportions of the different flows will be compared now. The natural cycle amounts to around 45 Gt C/a, which is split into a branch with the direct degradation of litter and a branch that runs through the soil carbon. In contrast, the two main anthropogenic influences currently amount to around 6 Gt C from the combustion of fossil and biogenic fuels and around 1.5 Gt C from slash-and-burn agriculture, although the numerical values fluctuate depending on the literature database used [85, 86]. As far as the uptake of these amounts is concerned, the subprogram for the ocean used in this work, which initially goes back to [87], shows an annual net uptake of around 2 Gt C/a. According to the present model, the annual increase in the atmospheric compartment resulting from the fluxes described above is approximately 2.7 Gt C/a (= approximately 1 ppm/a).

Added to this program structure is the so-called CO_2 fertilizer factor. This biochemical effect stimulates plant growth due to an increased atmospheric CO_2 content. A graphical representation of this formula for the fertilization factor, which also depends on the local soil quality, can be found in Figure 5 [68] as well as the graphical representation for all other important formulas mentioned.

Figure 5
How the fertilization effect is modeled in the CEBM



2.3. The sensitivities within the carbon cycle

2.3.1. Influence of the starting value for the atmospheric CO_2 concentration

Various runs at the beginning of the project with the target to doublecheck model sensitivities showed that the starting value for the pre-industrial atmospheric CO_2 concentration (287 ppm or even 285 ppm in 1860) that was assumed in the program did not have a noticeable influence on the final result. Rather, this (already very) small difference of 2 ppm continues to be preserved (almost unchanged) along several model centuries.

2.3.2. Influence of the length of the pre-run

As a basis for the simulations, two useful preliminary tests were carried out, with the time until settling of dynamics (relaxation time) for the carbon pools being 2,000 and 10,000 years, respectively. A very short pre-run period of around 100 years does not yet allow the carbon reservoirs to settle, as can be seen from Figure 6 [79] (center). Especially, the pool "soil organic carbon" (ASOCD) is the slowest and takes several hundred years to equilibrate, which coincides with the slow accumulation of soil in real-world biotopes.

2.3.3. Influence of different deforestation scenarios

The influence of various deforestation activities assumed for the future on the atmospheric CO_2 concentration (expectably) shows that a variation in clearing activity within realistic limits will have a noticeable influence on the atmospheric CO_2 concentration up to the year 2100, but that the resulting variation in this value in the year 2100 will only be in the range of around 50 ppm, in case deforestation scenarios are used with a theoretical maximum (i.e., all woods cleared until 2100) or minimum level (i.e., almost no forests cleared). This calculation result leads to the statement that global deforestation activity is not the most decisive factor for the CO_2 problem, although of course the severe global deforestation has an extremely negative influence on the earth's ecosystem, which is clearly stated but reaches beyond the mere C cycle.

2.3.4. Influence of the fertilizer effect

A still controversially discussed sub-topic of the carbon cycle problem is the so-called CO_2 fertilizer effect [71, 88–91]. An increased CO_2 concentration in the atmosphere leads to increased plant growth for two main reasons. On the one hand, the pores of the leaves open and, on the other hand, the partial pressure of CO_2 outside the cells increases, which shifts the reaction equilibrium of photosynthesis. However, this fertilization effect does not only depend on the external CO_2 concentration but also on a variety of other factors: existing or non-existent water stress on the plant as well as the quality of the soil, etc. The latter influence is taken into account in the CEBM by the fact that the level of CO_2 fertilizer factor is modeled depending on the soil quality (see horizontal axis in Figure 5).

There is a certain discrepancy in the available literature as to whether the fertilization effect only leads to an increase in plant growth (NPP) or also causes an increase in the standing plant mass (phytomass). In any case, both effects are assumed in the CEBM, which means that the world's plant absorption capacity for emitted CO_2 is overestimated rather than underestimated. With regard to the atmospheric CO_2 concentration, this means that the calculation results available here could increase slightly if the basic biological assumptions were changed.

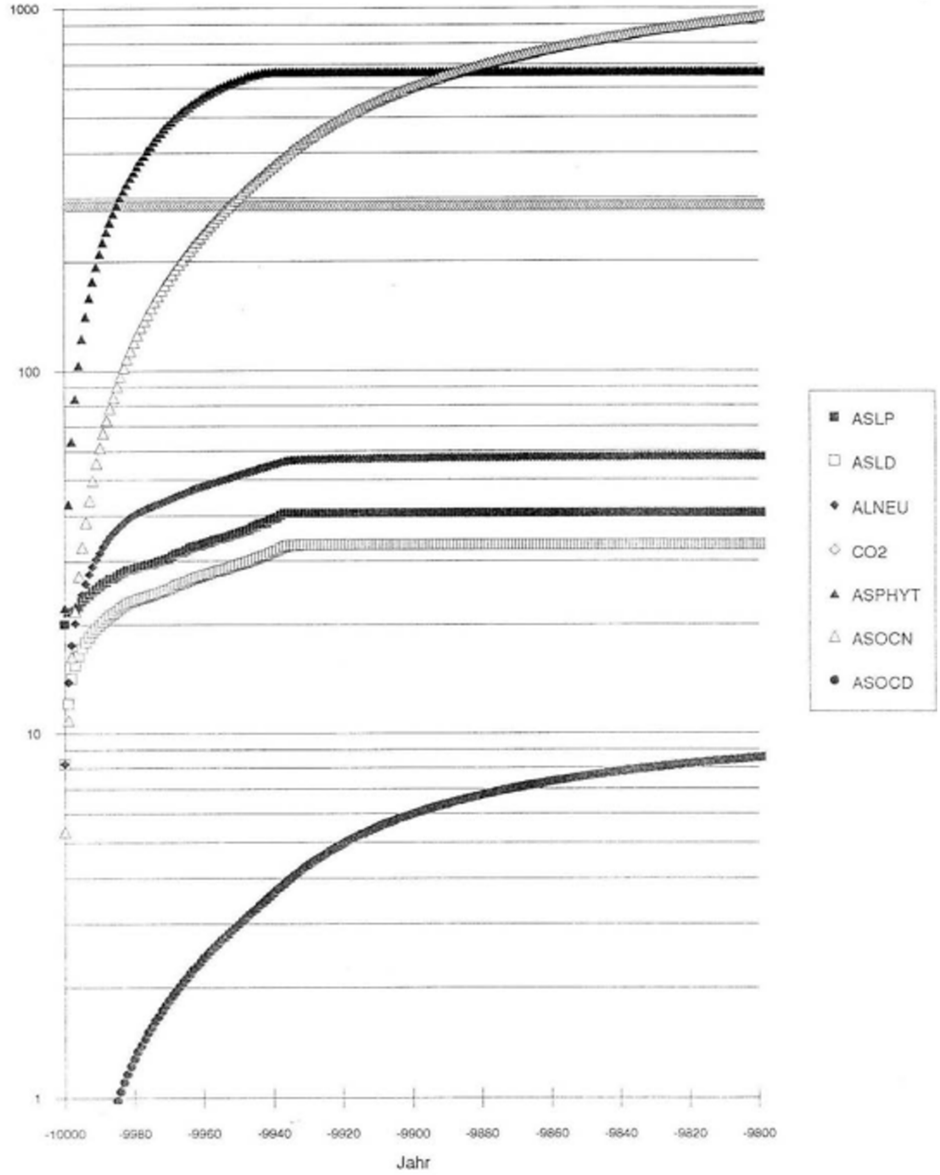
Regarding the quantity of carbon absorbed into the plant cover due to the fertilization effect, it should be said that, for example, a doubled pre-industrial atmospheric concentration of around 580 ppm in the CEBM would correspond to an increase in NPP by around 20% globally, that means a fertilization factor of 1.2. This results in an increase in the reservoir "phytomass" by the same factor. This amount of carbon is roughly comparable to the plant mass lost through deforestation since the beginning of industrialization. The conclusion can be drawn from these magnitudes that the remaining scientific uncertainty about the extent of the so-called fertilizer effect may have an influence, but not a decisive effect, on the final result of the CO_2 concentration levels in the atmosphere. A symbolic graphical illustration is provided in Figure 7.

2.3.5. CO_2 emission data for recent and older history

Data of fossil fuel emissions after 1950 can be obtained with satisfactory accuracy [86, 92], for 1860 to 1950, they are also available within the CEBM. A different situation arises for the previous emissions from traditional energy use of biomass (firewood and charcoal): On the one hand, there are little data in the relevant literature, but on the other hand, these data sources (e.g., UN Energy Statistics Yearbook, [93]) give the impression that the assessment bases changed from edition to edition of the annual statistics volumes and that the estimates are generally too low.

This at least sufficient certainty regarding the historical energy-related CO_2 emission data is offset by a much greater uncertainty regarding the historical deforestation data. The data for the areas deforested in each country (expressed as percentages) are inputted

Figure 6
How the pre-run allows for the dynamic equilibrium of carbon pools



into the CEBM starting from 1860 and are therefore part of the successful recalculation of the measurement curve for CO_2 since then, and a comparison with the literature was undertaken [94–98].

2.3.6. The assumption of stationary equilibrium

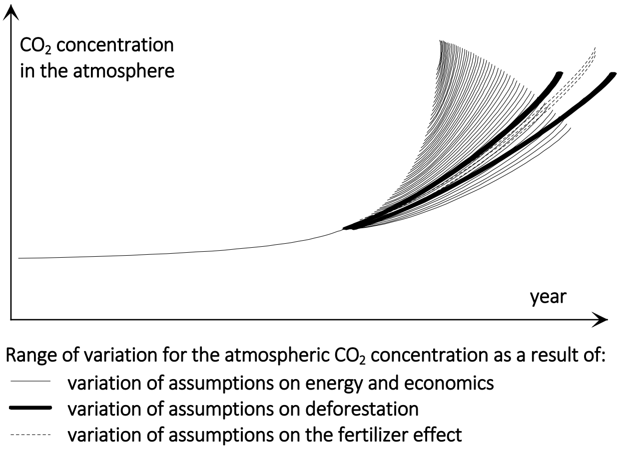
As already mentioned above, the growth processes of large forest areas, which are supposed to extend over several decades, for example, cannot be modeled by the CEBM with the exact temporal resolution during this period. Rather, it is assumed that planting operations such as clearing operations occur suddenly from one year to the next. These changes in plant cover are controlled in the CEBM by changing the area allocation percentages. For example, the deforestation process corresponds to a reallocation of natural to agricultural areas. The lower vegetation density associated with agricultural usage of areas compared to the natural vegetation results in a (sometimes very large) amount of carbon, which corresponds to the cleared plant mass and is therefore produced within one year.

In the opposite case of afforestation, it is assumed in the CEBM that the higher plant density corresponding to natural land use increases within one year. The delay of the real growth process to several years is ignored [63–65]. This means overall that the "phytomass" reservoir is calculated correctly in terms of quantity, but its temporal dynamics are slightly inaccurate.

The same complicated circumstances in the transitional stage of land use changes are reflected in the litter production to be modeled. Stationary equilibrium is also a guiding principle here. As mentioned, this is mathematically represented by equating annual NPP and litter production.

In particular, large-scale afforestation processes cannot be accurately represented in terms of their dynamics over many years, but the quantity of carbon stored in the plant cover through

Figure 7
Sensitivities of the atmospheric CO_2 concentration to various basic assumptions of the model



afforestation is accurately represented. The correct amount of CO_2 is removed from the atmosphere, but the time period for this year-long process is concentrated in the first year of reforestation instead of several decades. It should be noted that this small inadequacy of the model as found does not, or only imperceptibly, affect the final result of the CEBM computer program used for modeling biomass scenarios.

2.3.7. Data on the carbon content of the plant mass

To convert mass units of plant material into mass units C, the value of 45% for the carbon content is used for the total living phytomass. This value is compatible with the relevant literature and also coincides with ecosystem research.

A somewhat more difficult picture emerges in the "litter" compartment (i.e., leaves and branches falling down) because it is assumed to consist of lignin components (approximately "woody") and non-lignin components (approximately "herbaceous"). The lignin portion of the litter, which is more resistant to weathering, and the organic soil have a C content of 60%. From the law of conservation of mass for carbon, it follows that a lower C content than 45% must be set for the carbon content of the shorter-lived inventory waste because it does not contain lignin. This formula is shown graphically in Figure 8 or [68].

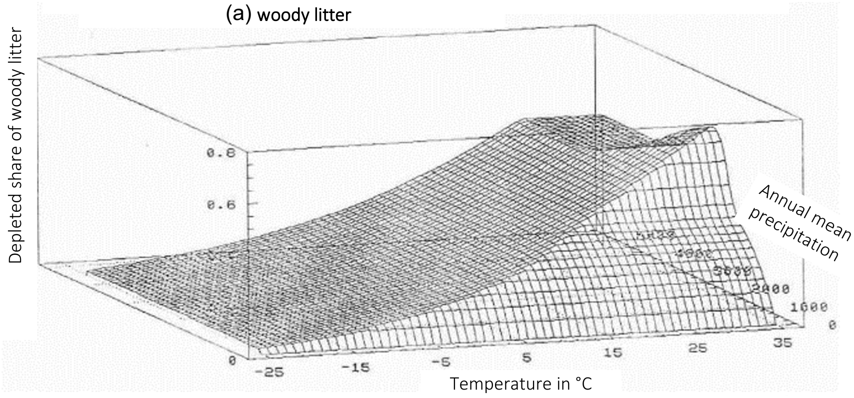
From the three-dimensional functional graphs of this mathematical relationship in Figure 8, the annually decomposed litter share of 10–80% can be seen as well that an incorrect assessment of the lignin content in the stand waste does not lead to a significant error in the carbon content in the short-lived stand waste. It can therefore be concluded that even slightly incorrect assumptions regarding the sub-aspect "carbon content of a plant" do not result in a significant error in the final result.

These and similar considerations were carried out as preliminary work before using the CEBM in order to increase confidence in the computational tool used and to test its suitability for assessing the net effect of biomass energy on the atmospheric CO_2 concentration.

Figure 8
Factors determining "herbaceous litter depletion" (LDH) and "woody litter depletion" (LDW) in the CEBM

The factors determining the depletion of woody and herbaceous litter in the CEBM

(a) woody litter



(b) herbaceous litter

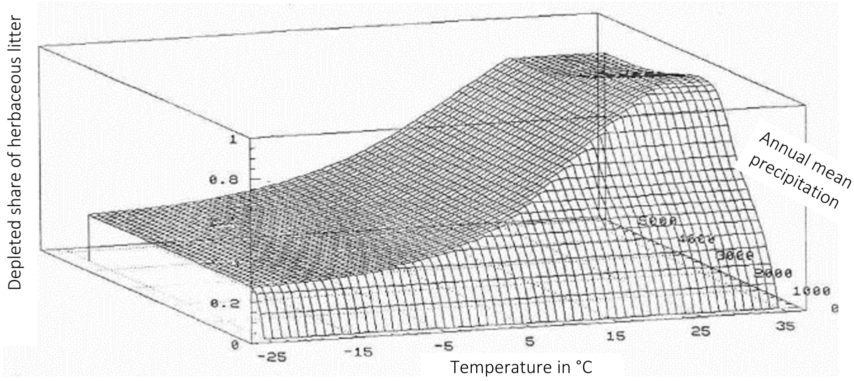
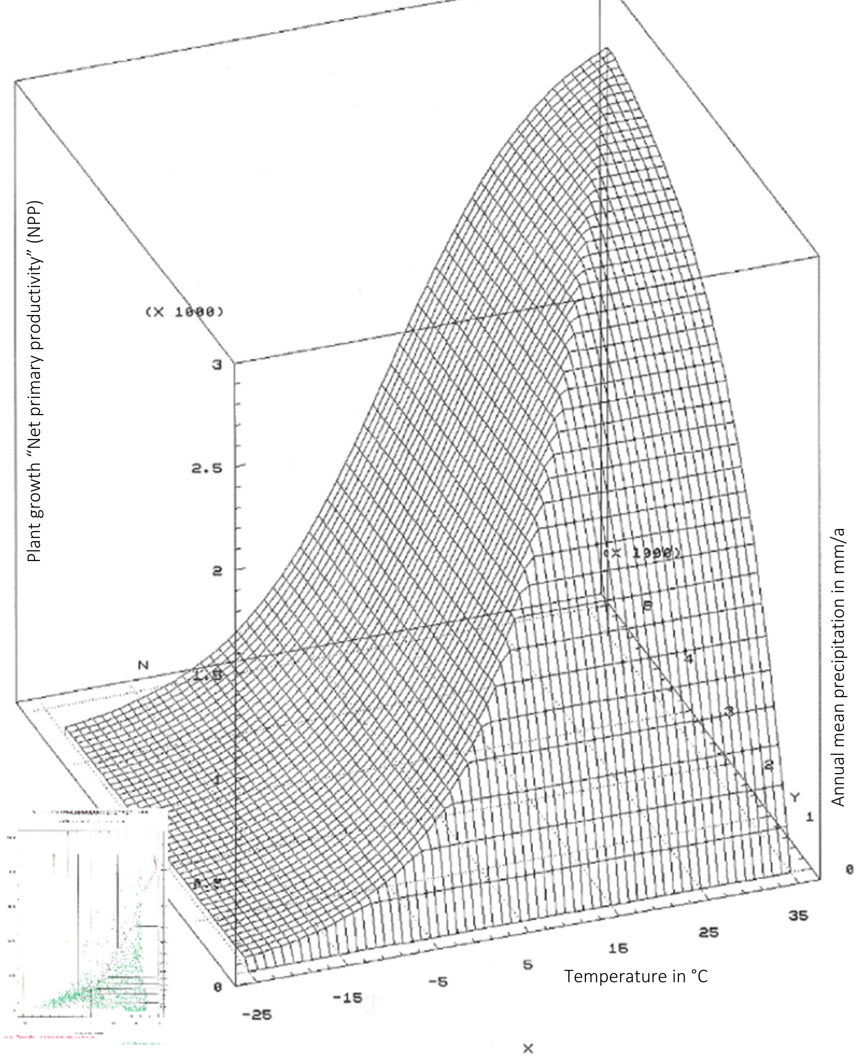
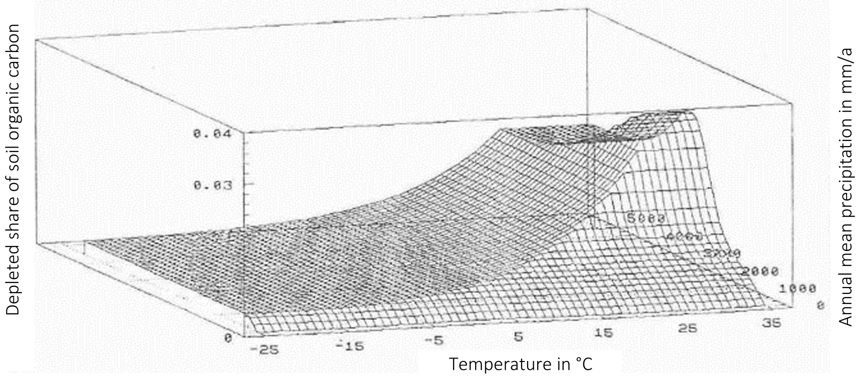


Figure 9
Factors determining "net primary productivity" (NPP) and "soil organic carbon depletion" (SOCD) (units are explained in the text)

(a) Net primary productivity (NPP)



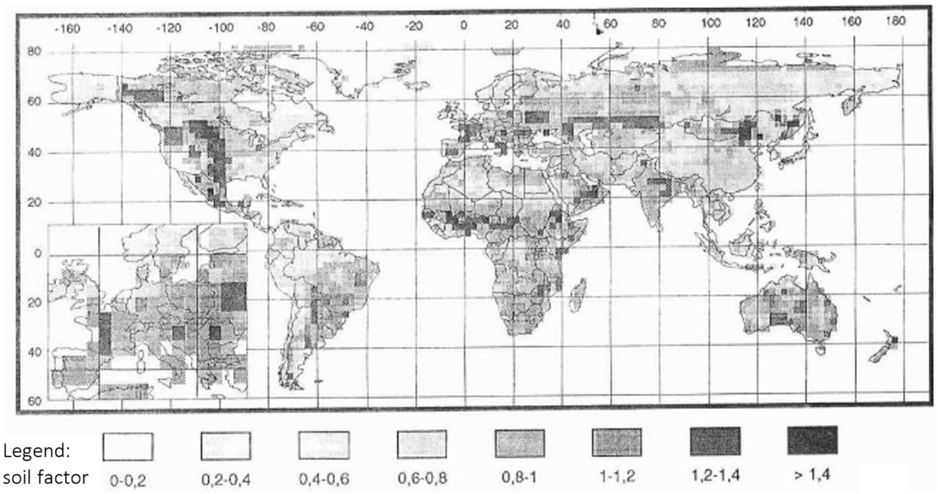
(b) Soil organic carbon (SOC) depletion



2.3.8. The formulas for growth and decomposition of plant matter

As already mentioned earlier, the mathematical expressions for the annual NPP and for the decomposition of the compartments of herbaceous litter, woody litter, and soil organic carbon (see the context in the two-color Figure 2) have the form of functions, which depend primarily on the local annual average temperature and the local annual average precipitation. These formulas go back to many years of development work by Gerd Esser, which is documented in detail [63]. In order to get a better impression of the quantitative connection for practical work with these formulas, the author created three-dimensional representations of the

Figure 10
The soil quality factor used in the CEBM for NPP



function graphs depending on temperature and precipitation in the first project phase. These are shown in Figures 5, 8, and 9 and [68] as a function of local temperature and precipitation. As expectable, biological activity increases in warm and humid climate areas.

In order to make it easier to read the numerical values, the small three-color insert in Figure 9 was created in contour line representation (= isoline diagrams), with the following meaning for the three colors: the function's value can be read from the black lines, the pairs of temperature and precipitation values that actually occur on the globe in the individual 2,433 grid elements are also shown as green dots, and the red line shows the border between temperature-limited and precipitation-limited domains as resulting from Liebig's minimum principle explained below.

As corresponds to Liebig's minimum principle (Liebig's law of the minimum: [99, 100]), which generally applies in biology, the so-called "limiting growth factor" determines plant growth. This is the amount of precipitation in dry areas and the temperature in cold areas. For orientation between these two areas, the boundary between temperature-limited and precipitation-limited zones is drawn as a red line in the small insert in Figure 9 and corresponds to the edge visible in all three-dimensional plots of Figures 8 and 9. At this edge, speaking in the language of analytical geometry, the isolines intersect at approximately right angles. The unit of measurement for NPP is grams of biomass/m^2/year (while 100 g/m² equals 1 t/ha); for the three degradation rates, the unit is percent * 100, hence dimensionless, meaning the share of the respective reservoir being depleted annually, ranging from zero to one. In medium latitudes of the planet, this share is around 40% for the decomposition of herbaceous plant matter, around 20% for woody plant matter, and around 5 per mille (= 5 thousandths) for the decomposition of soil organic carbon; which is in line with experience. In the latter cases, no distinction is made between agricultural or natural land use. A check with biologists (at an Institute for Ecosystem Research) showed that these numerical values do not deviate from expectations.

The theoretical NPP of natural vegetation for the temperate zones is therefore around 1,000 g/m²/a, which corresponds to an annual hectare yield of 10 tons of plant mass. This growth formula goes back to sources including [101, 102]. However, the result of the theoretical functional relationship mentioned for the NPP dependent on temperature and precipitation is not used directly in the CEBM as such, but the influences of soil quality in the relevant grid element are also taken into account. This is done using a dimensionless multiplication factor that represents the soil quality ("soil" variable). Only the values for NPP corrected in this way are used to calculate the annual carbon cycle. For readers interested in details, a wide-format map with the numerical values of NPP is also provided as Figure 10 [79] shows.

A visually clearer form of representation of Figure 9a is the world map in grayscale style for the NPP in Figure 10 above and for the corrected NPP in Figure 11 [79] below.

Since the sensitivities of the carbon fluxes in the CEBM are discussed in this chapter, it should be noted that a possible mis-estimation of the basic data of temperature and precipitation in a particular grid element is reflected as an error in the flux variables discussed here. The size of such an error can be seen from the 3-dimensional diagrams. However, the mathematical formulaic representation of complex growth and decomposition processes is also subject to errors: The diversity of biological processes certainly cannot be represented with one single clear mathematical function, which appears graphically as a geometrical surface in number space. Rather, the actual measured biological values obtained through real-life experiments form a more or less strongly scattered point cloud around this mathematically unequivocal surface. However, it is advantageous for the user of the CEBM to keep in mind the steepness of the functional surface in the value range, because this forms a measure of the sensitivity of biological realities under parameter changes.

Finally, the last four figures mentioned also have the value that one can provide a provisional but clear picture of the influence of a possible shift in the global climate on the carbon cycle, which is expressed through changes in temperature and precipitation values. For example, a global uniform temperature increase of 5 °C would correspond to a shift of the green point cloud (= actually occurring value pairs for temperature and precipitation) to the right by five graduation marks. The then changed values for plant growth must be read again; they increase particularly in temperature-limited areas of the earth. In a mathematically analogous manner, a change in global gross

Figure 11
Theoretical (above) and soil-adjusted (below) NPP

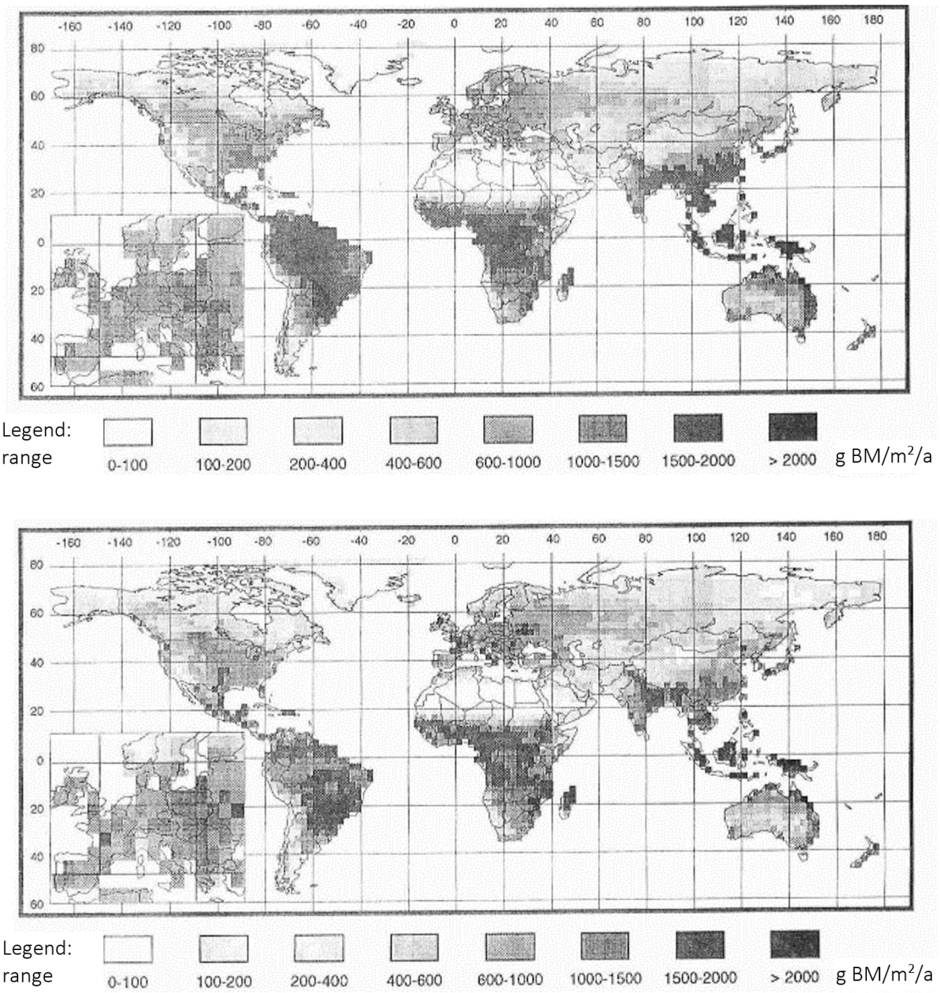
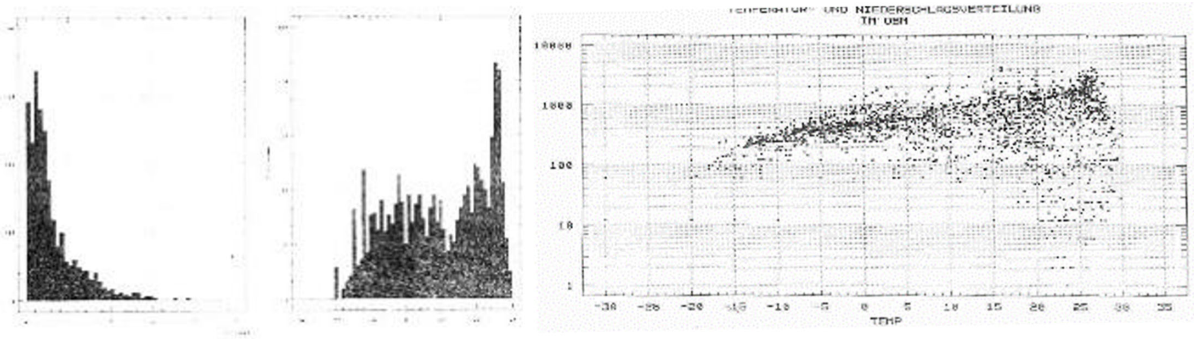


Figure 12
Statistical distribution of temperature (center) and precipitation (left) data in the CEBM grid elements, also plotted as data pairs (right)



precipitation activity (to the extent that it would occur uniformly, which is not the case) corresponds to a shift in the green point cloud on the vertical axis. However, it should be clearly stated here that the CEBM is not suitable for reflecting the exact changes in the plant species world after the occurrence of global warming associated with changes in temperature and precipitation (see frequency plots and data pairs in Figure 12 [79]) unless the results of climate models are used for this purpose. An attempt to do so is made in [63] However, the more precise simulation must be left to models built specifically for this purpose. Information on this can be found in the report from the Hamburg Max Planck Institute for Meteorology [103].

The above-mentioned deliberation is intended to express that the CEBM offers some, but not complete, possibility of representing the changed growth conditions for plants due to the greenhouse effect, and thus, when using a suitable climate model, the feedback loop "plant growth → CO_2 concentration → temperature → climate (including precipitation) → plant growth" can be reproduced in an approximate model. However, the complicated meteorological and biospheric processes that are inevitably associated with the occurrence of an increased greenhouse effect cannot be represented by the CEBM.

3. Research output and usability

3.1. Explaining the history of the carbon cycle

As explained above, global carbon cycle models have the aim to model growth and decay of plants, standing biomass, and deforestation of trees in a dynamic manner to monitor carbon flows. The CEBM [50, 68] is able to outline the historical development of CO_2 as a function of deforestation and fossil CO_2 emissions [85, 86].

An analysis of the geo-referenced deforestation activities in the style of a sequence of maps (similar to the above ones) shows spatial patterns with the expected emphasis on Third World countries in recent decades. A detailed review of different measurement results by the author is shown in Figure 13 [68] at the IIASA. The underlying geographic question is if it is possible to detect spatio-temporal patterns of deforestation activities.

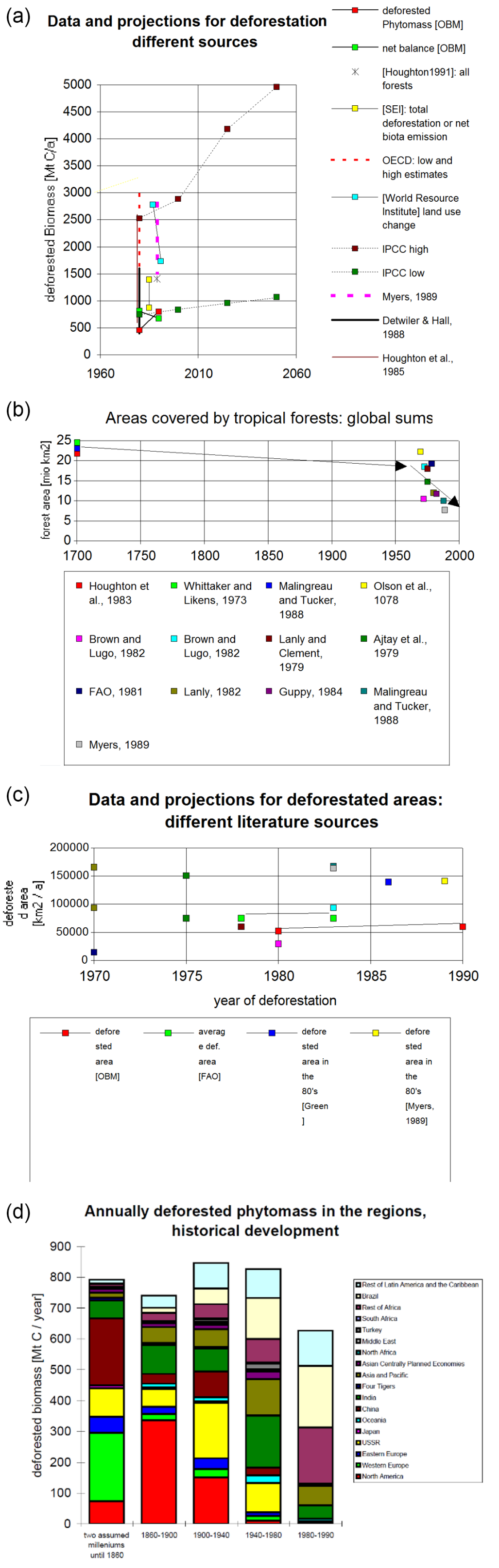
3.2. Interpreting historical cycles

The historical patterns of deforestation in different world regions are mapped as time series for the past century using over two thousand grid elements on the continents. The traditional way to map the historic development is to produce a sequence of such maps for different points in time. However, more of the historical dynamics can be discovered when providing graphs of regional aggregates and displaying them as timelines. Scenarios for future deforestation activities are necessary for global carbon cycle models and furthermore for climate change models, because global deforestation is the second largest driver of global climate change (after global fossil emissions). One very simple scenario writing method is to extrapolate historic deforestation patterns into the future.

When plotting the timelines of different world regions as Figure 14 shows [68], a pattern characteristic for each single geographic region seems to appear, namely an increase followed by a peak and then followed by a decrease in deforestation activities. These patterns start and end at different historical times for different spatial regions. In this light, the concept of "development phases" (differently shifted relative to time for different regions) seems helpful. Such a hypothesis could be named a meta-structure in the spatio-temporal dynamics of global deforestation.

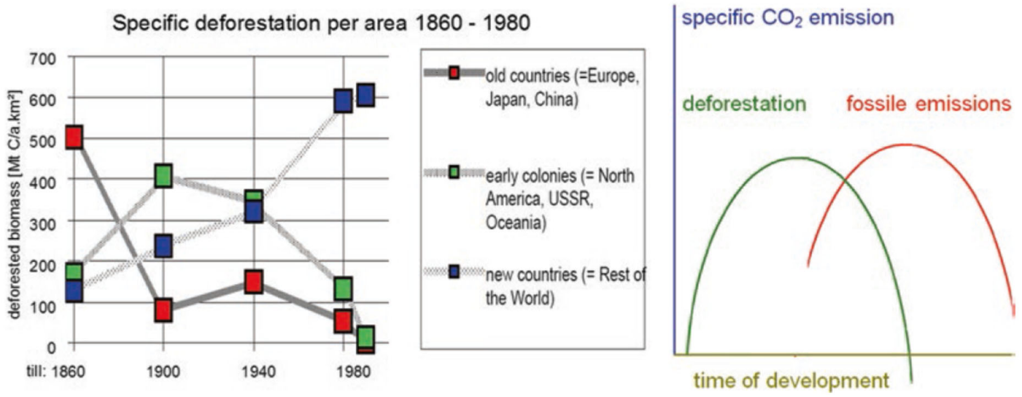
The detection of spatio-temporal patterns of deforestation activities [104, 105] is helpful in assessing likely future deforestation activities which cannot be restricted to a mere extrapolation of existing trends but are the result of a complex set of underlying driving factors. This case study thus suggests replacing "time" with "economic level," which might serve as a proxy variable for "evolutionary time."

Figure 13
(a–d) Historical development of deforested biomass by world region according to CEBM data



The principal question for these deforestation scenarios is: how do spatial patterns evolve over time and how do they change characteristically? Even if the pattern of the resulting parameter (here, deforestation) might seem to change in an enigmatic manner, the underlying driving parameters do change in a more understandable way ([68]). The perceived complexity of pattern dynamics can be reduced when (1) viewing dynamics not of the

Figure 14
Historic cyclicality in global deforestation patterns. Biomass by world region according to CEBM data



effect but of the drivers and (2) viewing dynamics not of the magnitudes but of their change rates.

3.3. Energy scenarios including biomass

Scenarios with the model described above have been undertaken [106–108] and are reported elsewhere [59, 68, 109] for reasons of limited space in this journal. Therein, the required framework is provided, namely the motivation to use various scenarios to cover global energy demand (growing at different annual rates, as a result of socio-economic assumptions) by an energy mix containing different percentages of fossil energy, non-carbon energy, and biomass energy as a result of steady transition processes in the countries' energy supply systems, especially in a view of technology assessment [15, 110] and with a view to very practical implementation even under strong geo-political stress [14, 111].

Recent years saw an intensive discussion of biomass energy [112–116] – while trying to avoid as much as possible the very costly option of "carbon capture and storage" (see [19, 117]) that is not tackling the problem at its roots – because this topic is important to doublecheck whether biomass as a readily-available [118–122], even if only transitory, bridging technology [123–125] is still reasonably viable when strictly requiring sustainability under economic restraints [126–128].

Main results of the CEBM are that in the long run, the pool of "soil organic carbon" is depleted as a result of the large-scale extraction of plant matter dedicated as biomass fuels. This key result is also corroborated by recent research [7, 16, 129].

In recent months, these key CEBM results were also positively commented in present-day literature [5].

4. Conclusion

This work represents a contribution to the long-term development of the human future with the help of quantified assessments. In particular, strategies should be sought to avoid the anthropogenic additional greenhouse effect and its huge social cost.

By means of the "CEBM," the influence of various energy scenarios and various biomass usage scenarios on the atmospheric CO_2 concentration up to the year 2100 can be evaluated. A detailed look at the global carbon cycle makes it clear that biomass as an energy source has decisive advantages over fossil fuels. The results of the model also clearly show that reducing the growth rates of energy demand is an essential prerequisite for actually achieving a climate-friendly development path and that, in addition to the use of biomass, solar systems should be used as further environmentally and socially compatible renewable energy sources to cover the then greatly reduced energy demand.

Based on model runs (described elsewhere, [68]), it was found that the following two CO_2 reduction strategies bring the same level of improvement compared to the (already optimistic) reference case with a future 1% annual increase in CO_2 emissions:

- By the year 2100, the entire naturally vegetated area on earth will be used to generate biomass energy. The annual increase in woody material is used to generate energy by combustion.
- The annual growth rate of CO2 emissions and the associated global fossil energy consumption will be reduced by half a percentage point from +1% per year to +0.5% per year.

From around 100 test runs with the CEBM and in particular the comparison of the two results mentioned, the following conclusion emerges regarding the preferred strategy for mitigating climate change: In view of the major disturbance in nature associated with the extensive use of biomass, the reduction of the global energy demand should be the first priority. The calculation results of this model show that only by reducing energy consumption (and thus CO_2 emissions) the expected atmospheric CO_2 concentrations can be reduced to values which (only) then can serve as a starting point for substitution strategies with other energy sources. However, maintaining current rates of increase in global energy demand reduces the greenhouse gas reduction potential of biomass energy to a comparatively marginal size. Additionally, considerations on material cycles clearly show that avoiding energy requirements is preferable to covering them even with carbon-free energy sources. Generally speaking, the turnover of matter associated with human life processes should be reduced.

In view of the CEBM results, the question of whether biomass should be strongly promoted as an energy source while maintaining sustainability can be answered clearly with "yes." The limitations of this diagnosis lie in the other material cycles connected to carbon, especially nitrogen, water, phosphorus, and minerals, which are not taken into account in the model formulae.

However, the question of whether the undesirable increase in CO_2 in the atmosphere can be prevented using biomass alone as an energy source can be answered clearly with "no."

Future research is needed regarding synergistic biospheric effects triggered by bioenergy, the admittedly high transformation losses (which are not yet included here), and finally the combined effects of the energy market after the ongoing introduction of truly carbon-free sources such as wind and solar.

Improvements for future global carbon cycle models can lie in including the synergistic interactions with other nutrients and material cycles as well as in reflecting the attached socio-economic conditions by either narratives or scenarios. Better geo-resolution will allow to model biospheric zones more realistically.

Recommendations

The findings suggest to evaluate the carbon neutrality of biomass fuels on the level of concrete conditions of growth, transport, processing, and harvest, in order to select practically suitable biomass energy strategies.

Several dedicated **policy recommendations** can be identified after interpreting the CEBM scenario results:

1. Safeguard sustainability requirements on a principal level in dedicated biomass energy plantations, including maintaining nutrient cycles, in order not to exploit these biotopes.
2. Maintain sustainability requirements in existing forestry on naturally grown areas in order to preserve biodiversity according to the local characteristics
3. Ensure short transportation paths from biomass growth sites to energy conversion sites in order not to hamper energy efficiency by over-proportionally high transportation demands
4. Ensure efficient energy conversion pathways (e.g., from raw biomass to bio-fuels) in order not to hamper overall system efficacity by high conversion losses.
5. In order to contain the systemic effect of soil depletion (which is described by the CEBM as existing on a principal level) make sure that within all biomass growth strategies the herbaceous litter such as leaves, twigs, barks, and other unused quantities of biomass is remaining on the sites in order to produce soil organic carbon to the highest possible level – to prevent long-term soil depletion as foretold by the CEBM.
6. Allow for double usage of areas needed for production of biomass energy, such as collateral agricultural usage or parallel usage for solar and wind energy generation
7. Integrate any biomass energy strategy into an overall strategy of energy conservation and energy efficiency, because otherwise the potentials for biomass energy will prove to be too low.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

Gilbert Ahamer is an Editorial Board Member for *Green and Low-Carbon Economy* and was not involved in the editorial review or the decision to publish this article. The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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