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How to Compute Whether Biomass Fuels Are Carbon Neutral

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Abstract: Based on recent interest and on the importance of the ongoing climate change catastrophe, this article provides the basics of global carbon cycle modelling as required for the assessment of the degree of carbon neutrality of biomass energy, and its underlying dynamics. It is aimed at clarifying the question "Are biomass fuels carbon neutral?". The "Combined Energy and Biosphere Model" (CEBM) computes annual carbon flows including growth and decay of plants on 2.5×2.5° grid elements of the continents' surface and offers detailed results on the changes of after implementation of large-scale biomass energy strategies worldwide. The main (and possibly unexpected) effect is the long-term depletion of the soil organic compartment after extraction of biomass fuels. When comparing CEBM model runs using (i) biomass energy sources and (ii) carbon-free energy sources (such as solar or wind), it becomes quantitatively clear already on the theoretical level (i.e., even without taking into account efficiency losses) that biomass is only "half as carbon neutral" as ideally assumed, to express a rule of thumb – mainly because of soil carbon depletion. Still, biomass energy will play an important role when fighting global warming, even if efforts to lower energy demand are preferable as a fundamental strategy.

Keywords: global carbon cycle; global model; biomass fuels; carbon neutrality; energy strategies; Combined Energy and Biosphere Model; CEBM

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1. Introduction

1.1. Motivation

In order to realistically fulfil the (existing and most urgently needed) global and national climate protection targets, all potential measures have to be implemented to a maximum extent. Given its immediate technological availability [1–9], biomass energy has been playing a key practical role for decades already, and was conceptually supported by the traditional assumption of its carbon neutrality: under sustainable conditions, carbon dioxide emitted during combustion was held to be equal to its absorption during plant growth [10–17]. However, in order to clarify conditions of carbon (C) neutrality quantitatively and more reliably [18–31], it became necessary to model the annual natural C cycle globally and to consider its changes as a result of steadily growing large-scale biomass strategies [32–40]. Because a recent publication [41] found much interest in readership, this article dwells still deeper into the dynamism of C flows and their alterations after biomass fuel extraction from the natural C cycle.

The present article contributes to solving the question: what type of global model do we need to assess whether biomass fuels are carbon neutral?

1.2. Relevance

Al efforts in the UNFCCC and IPCC frames and quite concretely, the recent "European Green Deal" [42] calls for quantification of the positive effect of various climate protection strategies on the CO_2 content in the atmosphere [43], including foresight methods [44]. The presented models offer support to achieve this goal. Especially because recent publications [41,45,46] receive interest [47], p. 2; [48–54], the present article undertakes to dwell more into modelling details on the global carbon cycle.

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1.3. Context

While global climate change is the wider context, the focus of this publication lies within both the themes of energy economic and biosphere modelling (letters E and B in the symbolic image for the "density of description" in the left half of Figure 1).

Contextualization of the carbon cycle within the frame of all existing and relevant cycles of matter (such as oxygen, nitrogen, phosphorus, minerals, water, but also energy and money) is shown in the right half of Figure 1.

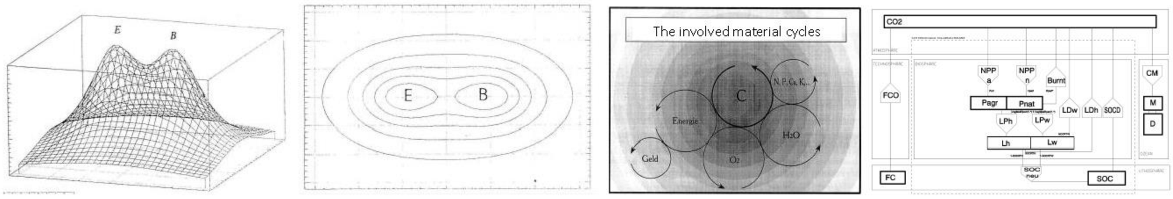

Figure 1. At far left and left: Conceptual density of modelling effort in the CEBM, as gravitating around the biospheric (B) and energy (E) themes, in 2- and 3-dimensional symbolic representation. At right: the carbon cycle is of course linked to many other material cycles, of which every reader is aware anyhow. At far right: sketch of the key flows and pools of the carbon cycle, including atmosphere, biosphere and ocean (45; 46; 55, p. 204, 166).

2. Materials and Methods

The next sections dwell on several model parameters which provide insight into the functioning of the CEBM and show their frequency distributions, geographic distributions and sensitivities.

2.1. Representation of the Model Parameters

In the following section, the various CEBM model parameters are discussed in order to provide an insight into details of the data basis of the "Combined Energy and Biosphere Model", the *energy-related* context of which was described recently as based on scenario techniques [74]. The biospheric part of the CEBM is based on detailed modeling while using the following *biospheric* data.

2.1.1. Basic Climatic Data

The two most important driving climatic parameters in this biosphere model are the annual mean temperature and the annual mean precipitation. A map display with eight levels of gray shades and numerical values is shown in Figure 2 for these two input data sets. Figure 2 shows the global distribution of the annual average temperature as a map (at left) and as a frequency distribution (at right), for both temperature (a) and precipitation (b).

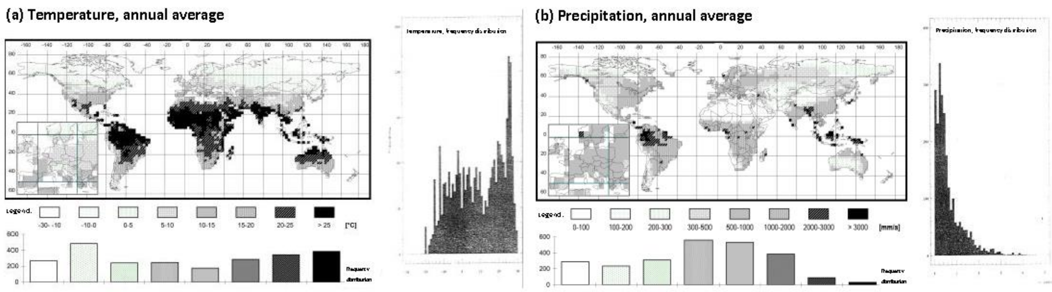

Figure 2. Temperature (a, in °C)) and precipitation (b, in thousand mm/a) as map and as frequency distribution, as represented in the CEBM. Data source of this one and all following figures: [41,45,55] based on [56,57]; all these and the following figures were created by the author.

The frequency distribution for the global precipitation values shows an approximately logarithmic-normal distribution, while the frequency distribution for the global temperature

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averages shows a pronounced two-peak distribution (see frequency diagram inserts in Figure 2). Such a non-uniform distribution must be taken into account when choosing the intervals for sensitivity studies of both parameters.

2.1.2. Basic Biological Data, Net Primary Productivity (NPP) and Phytomass (P)

The variable "soil" is used as a dimensionless multiplication factor to describe soil quality and can be found in grayscale representation in Figure 3 at left. A frequency distribution of these values, which vary from 0.4 to 1.7, can be found in the representation of the CO_2 fertilizer factor in Figure 3 at center. The geographical distribution of this soil quality factor "soil" shows a very disparate picture. As expected, desert areas (e.g. Sahara and Central Asia) show low values for this multiplier for net primary productivity. A value of soil = 1 means that the theoretically calculated NPP according to the formula from Lieth and Aselmann [58,59] is used in the CEBM without correction. Values of soil > 1 mean that the NPP actually used in the model is greater than that of the stated theoretical formula of the preceding so-called Miami model (pictured in Figure 4). The variable soil is therefore dimensionless.

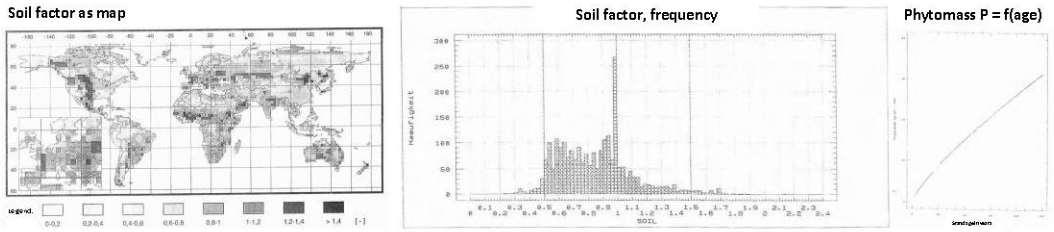

Figure 3. At left: Soil quality as map, as represented in the CEBM. At center: its frequency distribution. At right: the formula of phytomass as a function of stand age. Data source: as in Figure 2.

There are several ways to visualize the formula for theoretical NPP (which in itself consists of various exponential term that do not lend themselves to immediate practical interpretation). Figure 4 shows from left to right NPP first as a function of temperature, then as a function of precipitation, then as a contour plot as a function of both (while offering the green dots for the distribution of "temperature-precipitation" data pairs and finally as a comparison with decomposition of herbaceous litter – to highlight the slightly different biological dynamics of growth and decomposition processes.

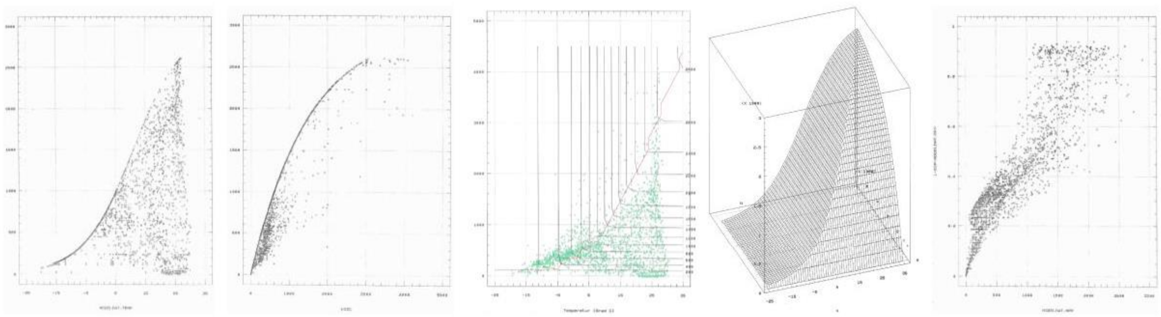

Figure 4. NPP, from left: Functional pattern as f(temperature), functional pattern as f(precipitation), and of both in 2- and 3-dimensional representation; at right: comparison with litter decomposition rates. Data source: as in Figure 2.

To describe the amount of matter in the standing natural plant cover (i.e., phytomass P, which represents a carbon *pool*), it is not exactly sufficient to use the annual net primary productivity NPP (i.e. the effective plant growth, which represents a carbon *flux*) according to the above-mentioned growth formula, but also the so-called stand age (Figure 5 at left) intervenes here. Incidentally, an essentially multiplicative combination of both values forms the value for the phytomass, a graphical representation of which is given in Figure 3 at right. Depending on the vegetation zones, the variable

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stand age takes on larger values (e.g. tropical or boreal jungle) or is close to 1 (meaning years) when it comes to grasslands and steppes (Figure 5 at left). This term means the average age of the standing mature natural plant cover, which indicates the time period required for growth to reach a stable flow equilibrium in a specific vegetation zone. Since the stand age variable is reflected in the "existing plant mass" variable, the geographical distribution given here reflects the geographical distribution of the plant population (as density, Figure 5 at center). As expected, the tropical rainforest areas as well as the temperate zones in Eurasia, the eastern USA and the Far East show a high stand age in the natural phytomass in the range of 100 years and above.

For reasons of comparison, the map of density of agricultural phytomass is added in Figure 5 at right, with foci in industrialized areas and Southeast Asia.

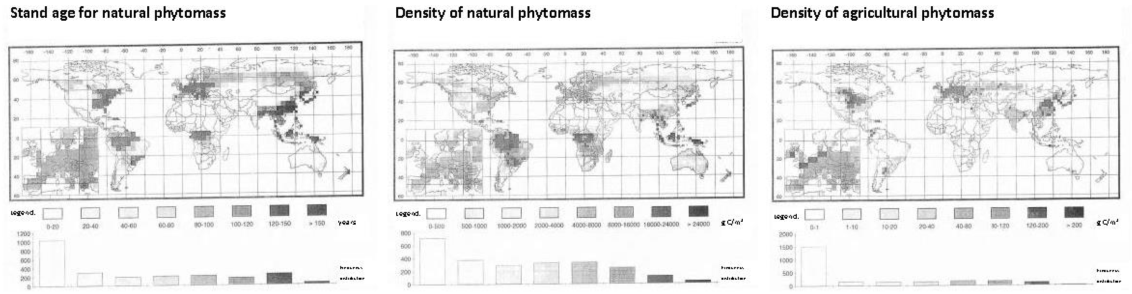

Figure 5. From left: stand age for natural phytomass, density of natural and agricultural phytomass. Data source: as in Figure 2.

2.1.3. Decomposition of plant matter (LD and SOCD)

After growth of plants and standing plant matter, the next item in the natural carbon cycle (Figure 1 at right) is the decomposition of plant matter by microbial processes. The values for the annually degraded shares of herbaceous and woody litter are also shown graphically, as they again result from heuristic formulas deduced from global synoptics of measurements (Figure 6, in 3-dimensional representation). Figure 7 provides the 2-dimensional representation regional distribution and comparison by regression with other parameters. As mentioned, both Figures show the two- or three-dimensional representations of the degraded proportions as a function of temperature and precipitation because these heuristic functions have a key role in controlling the global carbon cycle.

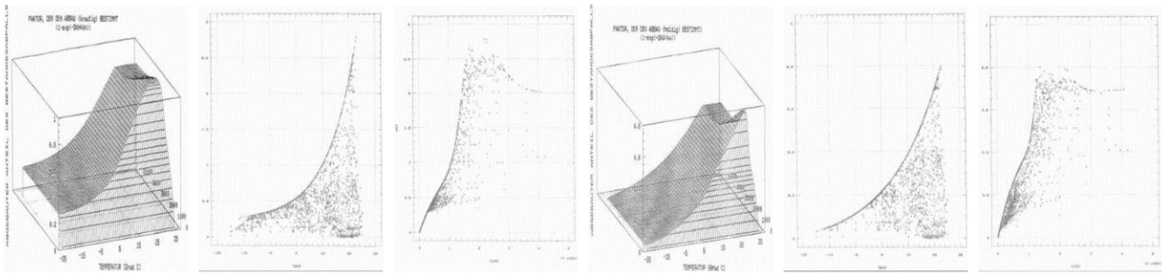

Figure 6. Litter decomposition, in two groups of three images, first for herbaceous litter, second for woody litter. From left: as a function of both temperature and precipitation, as f(temperature), and as f(precipitation). Data source: as in Figure 2.

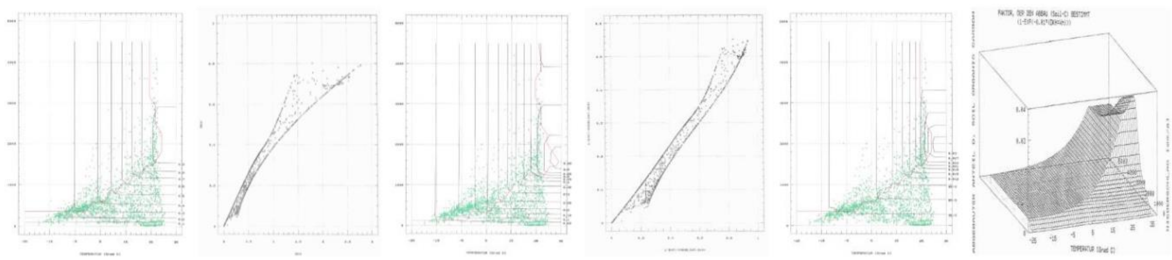

Figure 7. Litter and soil decomposition, in three groups of two images, first for herbaceous litter, second for woody litter, and third for soil organic carbon (SOC). From left: in the form of a contour plot as a function of both temperature and precipitation, then as a correlation with litter decomposition. Data source: as in Figure 2.

Furthermore, the biological type of standing vegetation is determined in the CEBM by the "vegetation factor" which indicates the proportion of herbaceous plant mass in the total plant mass. It varies from about 30 to 100%, as can be seen from the map illustration in Figure 8 at left. This value will be relevant for the biomass fuel scenarios because the woody but not the herbaceous component is used for combustion in several scenario types. Areas with a high herbaceous content coincide with the well-known desert areas of the world: Sahara, Arabia, Central Asia and central Australia, southwest Africa, the Midwest of the USA and finally the coldest continental areas of the world in the north. If you read this figure the other way around, i.e., looking for areas with a high proportion of wood in the plant mass, you will see mainly the three tropical areas (South America, Central Africa and Indonesia) as well as the temperate belt of the northern hemisphere.

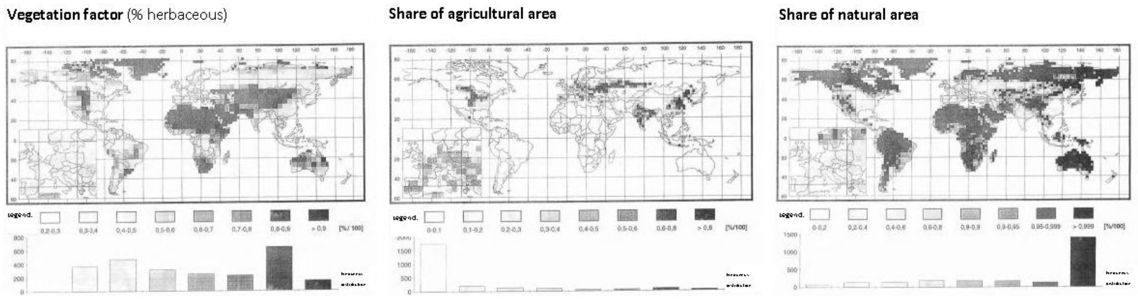

Figure 8. Vegetation factor in the CEBM denoting the percentage of herbaceous plant matter (at left), the percentage of agricultural area at center and the percentage of natural area at right. Data source: as in Figure 2.

Furthermore, the division between naturally vegetated and agriculturally used areas is of great importance: The variable shown in in Figure 8 at center indicates the proportion of agricultural area in the total area of the respective grid element, which adds up to 100% with the natural area share. From this map it can be seen that these areas largely correspond to the settlement zones of humanity. For the sake of completeness, it should be noted that areas used for meadows or pastures also fall into the category of agriculturally used areas; this area share lies between 60 and 100%, particularly in some areas of Europe, Ukraine and to the east, in Eastern China, India and the American Midwest. As a mirrored image of the proportion of agricultural areas, Figure 8 at right shows the proportion of naturally vegetated areas in each grid element: in the overwhelming majority of grid elements this is more than 99%.

Finally, agricultural productivity, which differs from natural productivity, is indicated by a separate input variable, which is assumed to be almost evenly distributed within a country (Figure 9 at left). By the way, in grid elements where the agricultural area share (Figure 8 at center) is zero, the value for agricultural productivity (Figure 9 at left) is also allowed to be zero. Figure 9 at center and at right offers a possibility to compare the geographic pattern of agricultural productivity with the geographic pattern of natural productivity (while these use slightly different units for their map representation).

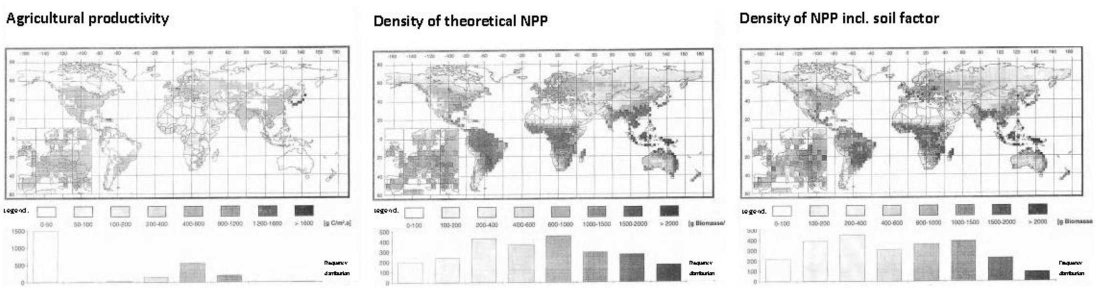

Figure 9. Agricultural productivity (at left) and the natural productivity without (at center) and with soil factor influence, in the CEBM. Data source: as in Figure 2.

With the help of the additionally entered variable " for the geometric (i.e., geodetic) area of a grid element on the earth surface and the variable of agricultural productivity, it can be computed that globally around 16.3% of the continental area (excluding Antarctica) is used for agriculture.

2.1.4. Political and Economic Input Data

The structure of the program structure in the CEBM determines that each grid element corresponds is assigned to one of 119 states. On the computational level, it cannot be the case that a grid element belongs partly to one state and partly to a neighboring state. Although this predetermined program structure may be detrimental to data accuracy in very small countries, it does not noticeably affect the global final result due to the large number of grid elements.

The country classification mentioned is used for the entire energy strategy program module and will be important there. As mentioned, the coarse grid can lead to data inaccuracies in small states because the exact geodetic localization of the state borders does not correspond to the borders of the grid elements. Sometimes a grid element contains several countries (e.g. the Benelux countries, containing Belgium, The Netherlands and Luxemburg). The grid element for Austria is located northeast of Vienna. As an example, the width of the Alps is only two squares, which leads to climatic uncertainty. If one wishes to use biospheric data for individual small countries, it is important to take into account that the numerical values must be adjusted, at least because of the artificial geometric rectangle area, which is different from the actual country area. Likewise, most accurate databases on deforestation, economy and energy supply are broken down by country.

2.1.5. Historic CO_2 Emission Data

The global sum of *energy-related fossil CO 2 emissions* from 1860 to 1988 is given based on the very useful available source [60] and subsequent updates, which includes a country-by-country breakdown of carbon emissions annually since 1950 and was published at Oak Ridge National Laboratory (ORNL). This data, differentiated by energy source, almost seamlessly continues the data that has already been available in the CEBM since 1860 into the recent past [61]. The only carbon-containing energy source not taken into account in this data source, but very important, is the energetic use of biomass that has been ongoing since the beginning of human civilization, which is referred to as “traditional biomass” in CEBM’s energy scenarios [62], p. 59-64.

2.1.6. Input Data for the Energy Strategy Module: Population and Economic Growth

Energy scenarios were described in much detail elsewhere [62], p. 301-310; [41,63–65]. For the detailed energy scenarios for the CEBM, a completely new program module was created. The data required for energy economics is not broken down into grid elements (as the biospheric data) but rather into countries because these form meaningful energy economic units given the same energy policies applied. However, it would still be possible to transfer this country-wise data to the level of grid elements with the help of a database created by the author containing the population distribution of the earth. For this purpose, the population density from an atlas was entered for each grid element [66], which was used as the best after having compared three atlases.

The result of this process, namely the global distribution of population density, can be seen in Figure 10 at left. With the help of this population database, it is now possible to distribute country-by-country data (e.g. emissions) approximately accurately (but sufficiently accurate, for the global model’s targets) across the area within a state according to the population distribution (for results see, for example, [62], p. 60-64). In addition, the information for the annual rate of population increase in the individual countries (which is assumed to decrease by 1.6% annually to provide results consistent with the UN estimate; [61]; [55], p. 113, taken from the same data source is shown in [67]; [55], p. A11/3 and in in Figure 10 at center while the scenario for the 2100 population distribution is shown in Figure 10 at right – showing a massive shift of earlier centers of gravity.

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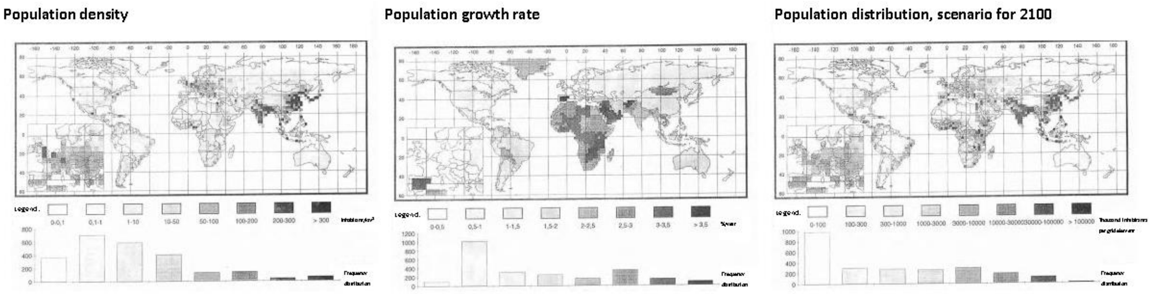

Figure 10. At left: Population distribution (as an auxiliary variable, to allocate country-wise data to grid elements) in the CEBM. At center: population growth rate, and at right: estimated 2100 population distribution in the CEBM. Data source: as in Figure 2.

The connected estimation of GDP growth includes saturation effects within the richest nations [55], p. 118 which conforms to both experience and the sustainability paradigm of saturating material turnover. Resulting economic levels (measures as GDP/capita) are pictured in Figure 11 at left, and resulting geographic patters of GDP per grid cell in Figure 11 at right. Energy scenarios resulting from these socio-economic patters are discussed in detail in [68–71].

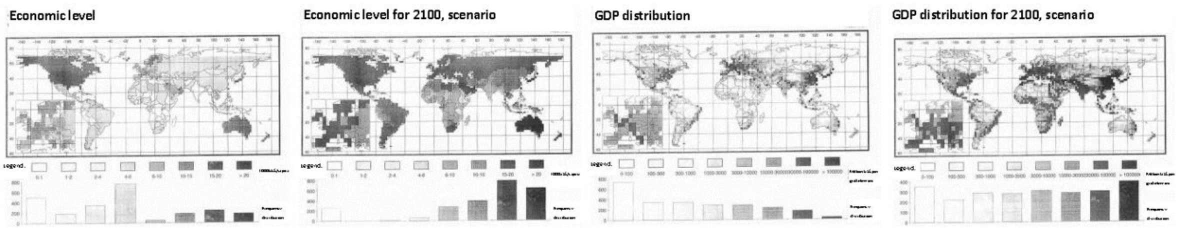

Figure 11. At left: Economic level at model start and in 2100 in GDP/capita; at right: GDP distribution in GDP per grid element at model start and in 2100 in the CEBM scenarios. Data source: as in Figure 2.

In order to provide an overview of the main model parameters, Table 1 lists the key global parameters, of which many are pictured in this article as a timeline.

2.2. Checking Accuracy and Sensitivities of Various CEBM Program Parts

In the following section, the various CEBM model parameters are discussed in order to provide an insight into details of the data basis of the "Combined Energy and Biosphere Model" (compare the list in Table 1). For a quick start, it was doublechecked whether the historic (and thus experimental) data path of atmospheric CO_2 concentration values was correctly modelled ("ex post") by the CEBM, which could be clearly answered by "yes" (thus, no figure, see [55], p. JB91-6. Furthermore, early enough the plausibility of the dynamics, elasticity and resilience of the ocean subroutine was assessed [55], p. A5-1-5, a user-friendly macro for creating geographic maps was created by the author [55], p. A6-1-8, the plausibility of the used country-wise emissions data was doublechecked [55], p. A7-1-5, and the arithmetic appropriateness of the biological formulas governing the carbon cycle was evaluated through graphic representation [55], p. A8-1-18.

2.2.1. Sensitivity Studies through Preparatory "Zero Runs"

In order to demonstrate the computational efficiency of the CEBM as a hypothetical historic study, fossil emissions or emissions due to land use changes or both were set to zero (these start in 1860). The latter calculation variant (i.e., without any anthropogenic CO_2 emissions) actually showed a constant atmospheric CO_2 content (meaning that the CEBM program did reach the required state of equilibrium within the natural annual carbon cycle). The other two mentioned test runs make it possible to dissect the influence of fossil emissions and deforestation emissions on the historical increase in CO_2 into two separate effects. It turns out that until 1900, agricultural emissions mainly

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contributed to atmospheric CO_2 (Figure 12 above left). Around 1950, both sources contributed equally, and later fossil emissions contributed significantly more to the rise of atmospheric CO_2 concentration levels. Similar signals within a hypothetical (i.e., only partially disturbed – as a historic what-if analysis) carbon cycle emerge in the global pools of phytomass (above right in Figure 12) and in litter as well as organic soil carbon (below in Figure 12).

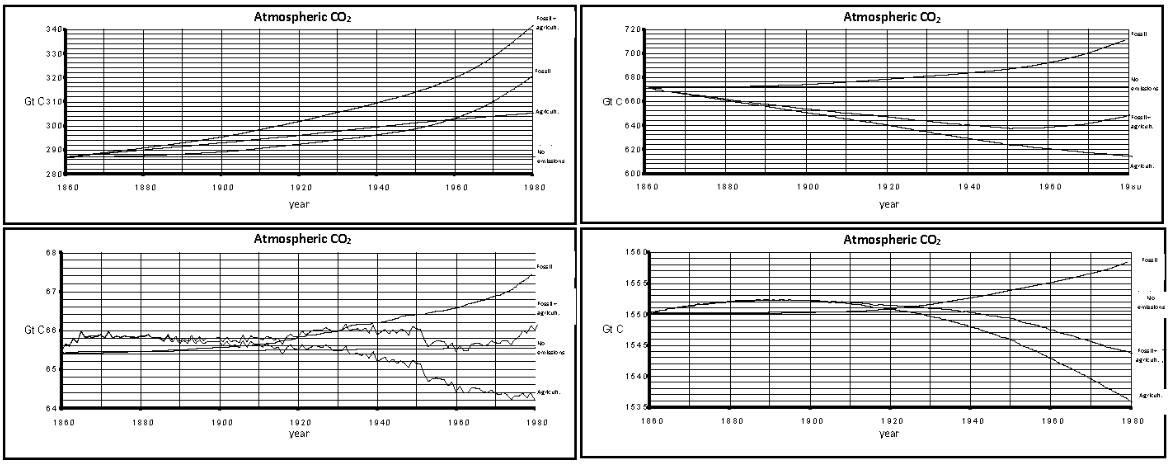

Figure 12. Computational separation of the contributions of fossil and land clearing emissions to CO_2 in the atmosphere (above left), to global phytomass (above right), to global litter (below left), and to global soil carbon (below right). Data source: as in Figure 2. Images are created by the author.

Moreover, Figure 12 above right shows that the fossil emissions seem to have resulted in a fertilization effect that increased the stock of global phytomass in the model by over ten percent (in case the used formulaic representation of the fertilizer effect is that exact). However, through deforestation, this phytomass was decimated by more than this same amount. The timeline of the variable litter, on the other hand, is more complicated: until 1900, the clearing contributed to a slight increase (biomass remaining on the ground after the clearing process), from 1900 onwards this compartment decreased compared to the standard run because of the lower phytomass in absolute terms (Figure 12 at below left). The same applies to organic soil carbon SOC (Figure 12 below right).

This modeling of an "imaginary history" in which only one of the two main CO_2 emission sources would have existed can serve to better understand the effect of future human interventions in nature.

2.2.2. Sensitivity Studies as a Result of Different Deforestation Scenarios

One of the key sensitivities of the modelled global carbon cycle is certainly its response to diverse deforestation scenarios. These can differ quite widely theoretically (i.e., just for arithmetic reasons, not to illustrate realistic practicability), namely ranging from maintaining the current plant cover to complete elimination by reckless total deforestation of the entire planet.

Figure 13 shows the eight different deforestation scenarios which are based on the principal understanding that deforestation activities in a grid cell are influenced by previously occurring deforestation activities in neighboring grid cells, but with variable probabilities of geospatial propagation. The amount of biomass burnt immediately in a given year (at left in Figure 13) results in an even larger amount of biomass that decomposes according to the existing formulas for plant decomposition, thus picturing the longer-term effects of destruction of a forest. Figure 13 at center shows the standing plant matter which in the year 2100 varies from ten to eighty percent of the existing amount, while scenario number 5 is the most optimistic scenario (in the sense of preserving forests) and scenario number 3 the most pessimistic one. Figure 13 at right shows the resulting atmospheric CO_2 concentration until 2100 which interestingly does vary but not enormously, when comparing to the variations caused by scenarios with diverging fossil emissions [62], p. 307.

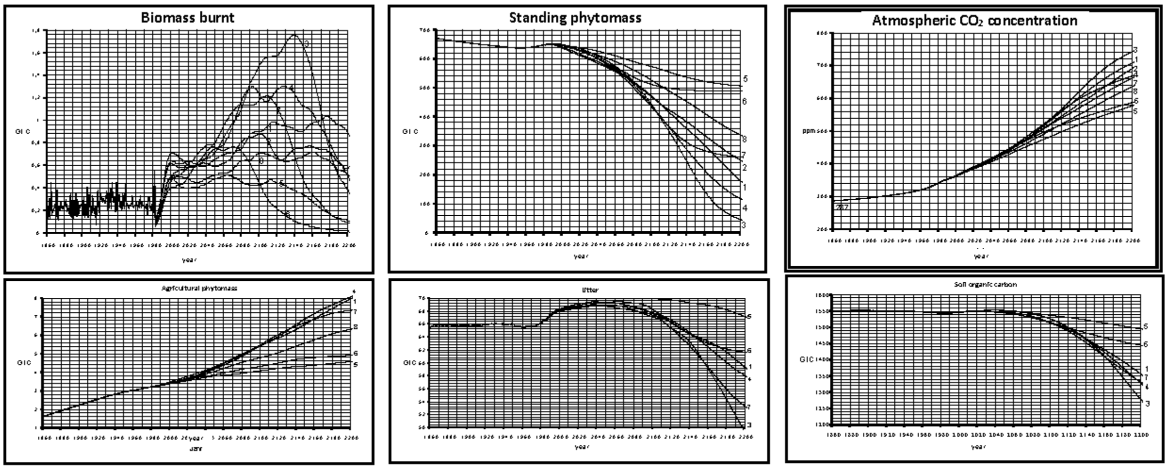

Figure 13. Above, at left: Comparison of the effect of eight (theoretically possible as a maximum, but practically unrealistic) deforestation scenarios (with an underlying increase in fossil emissions of 0.25%/year) on three biospheric parameters, as modelled in the CEBM. At left: the biomass burnt annually fluctuates according to the scenarios. At center: the standing phytomass decreases almost not at all (very optimistic scenario number 5) or even almost completely (very pessimistic scenario number 3). Below, some auxiliary parameters, starting from at left: global agricultural phytomass, litter, soil organic carbon. Data source: as in Figure 2.

2.2.3. Assumption of a Uniform Atmosphere

Since the global earth's atmosphere mixes within 1 to 2 years [72], the assumption of a single numerical value for the CO_2 content in the entire earth's atmosphere is justified for the calculation accuracy required here. The seasonal fluctuation in CO_2 content detected by measurements due to the growth and decay of plants in the annual cycle (including the iconic and historic Mauna Loa experiment curve) is not taken into account in this model on a monthly basis, but this does not affect its suitability for solving long-term energy management issues. Likewise, a CO_2 concentration gradient from the northern hemisphere to the southern hemisphere can be verified experimentally [43]. However, the resulting concentration difference between north and south is very small e.g., compared to the increase in concentration over several decades. For this reason, it is also justified that the regional distribution of energy-related CO_2 emissions on the one hand and CO_2 absorption by the oceans on the other hand is not modeled at the grid element level in the CEBM.

2.2.4. The Biospheric Carbon Fluxes

The degree of validity or accuracy of the *formulaic relationships* in the CEBM will now be examined.

With regard to the formulas for growth and degradation of plant matter, it can be seen as confirmation of the accuracy of the CEBM that a value of around 660 Gt C for the "phytomass" reservoir occurs in the steady state during the preliminary run, as is compatible with literature [59,73]; [74], p. 5. The same applies to the litter pool (approx. 70 Gt C) and the soil organic carbon pool (approx. 1,550 Gt C) reservoirs. An advantage of the CEBM as compared to other models discussed earlier [74], p. 3 is the distinction between herbaceous and woody biomass. A graphical representation of the comparison of the two degradation constants with one another or the shares of biomass degraded with one another can be found in Figure 7 (2nd and 4th from left). This shows that as a rule of thumb, herbaceous biomass is decomposed about 2.5 times more (or faster) than woody biomass. Of course, the rate of degradation is also correlated to a certain extent with the net primary productivity of the natural vegetation, which is shown in the rightmost image in Figure 6.

On the other hand, the mathematical representation of soil carbon degradation in the model suggests that exact information for such complex processes is difficult to find: the degradation rate for soil organic carbon is one hundredth of the degradation rate for herbaceous stand waste (Figure

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7 at right). The resulting flows for the degradation of soil carbon correspond to the expectations of experts in ecosystem research [58,59,73,75,76], but may represent only one of several possible attempts at quantitative description. In this context, attention should be paid to the complex processes involved in mineralization (degradation of organic material through microbes) in the different soil layers. The extent of this degradation depends on many local factors that are difficult to describe in a global model in their local details.

2.2.5. The Ocean Model

Since the thematic core of the model is in the area of biospheric cycles and not in the area of oceanic carbon cycles, a simplified model was used to model the CO_2 absorption processes in the global ocean. The physical process of the diffusion of CO_2 into the several assumed deep layers of the ocean is modeled in a dedicated sub-program. However, other approaches to modeling processes in the ocean can also be found in the literature, which are listed below according to the degree of spatial differentiation:

1. The model used in the CEBM is a one-dimensional "box-diffusion model" with spatial resolution only in the vertical axis, but not along the earth's surface (see Figure 14 at left and second left).
2. A first improvement would be the differentiation into different latitudes (two-dimensional models). Here the global ocean is divided into ring-shaped zones surrounding the globe. CO_2 diffusion also occurs between the various ocean rings. Each of these sub-oceans is assigned the corresponding geographical extent, which comes from the distribution of the continents on the globe.
3. Two-dimensional "upwelling" models: In addition to diffusion, vertical mechanical mixing of the ocean's water masses is assumed. This also means that carbon is transported in the form of CO_2. An example of this is the model designed [78] at IIASA. This also has a "wind-driven" component, which models the movement of oceanic water masses due to wind activity. The flow conditions are shown in Figure 14 at third left, where only the northern hemisphere is taken into account.
4. Three-dimensional ocean models with spatial resolution in all three coordinate directions are being developed, for example, at the Max Planck Institute in Hamburg (MPI) for Meteorology. Horizontal flows circulating around the globe can also be depicted (see Figure 14 at fourth left). Such models are connected to the "High Resolution Biosphere Model" (HRBM) by [77] as part of the European carbon cycle modeling program ESCOBA [78–81]. The reference value of 1.8 Gt C can serve as a guideline for the absorption capacity of the model ocean of the Max Planck Institute (MPI) Hamburg according to an oral communication by authors Heimann and Meier-Reimer at MPI. This value is slightly lower than the value of the model ocean used in the CEBM, and thus seems consistent.

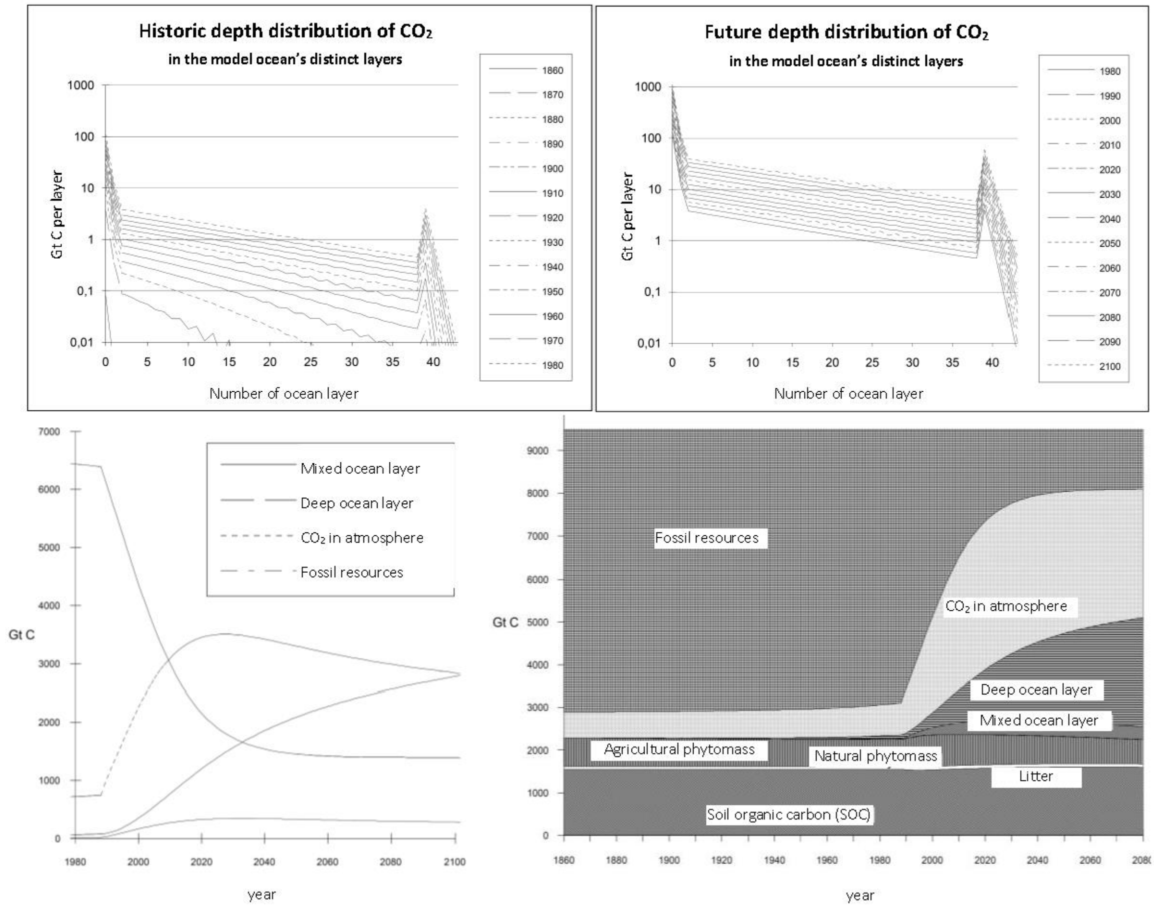

Figure 14. Above: Depth distribution of CO_2 in the model ocean (with layers of different depths) until present (at left) and after present (second left). Fourth and fifth: behavior of the CEBM model ocean after an artificial CO_2 emissions pulse, to test the response. Data source: CEBM. Images are created by the author.

As a principle, different chemical reactions have different characteristic reaction times. As an examle, CO_2 can be absorbed by the atmosphere within a few years while the complete resorption of elevated atmospheric CO_2 concentration my take much longer because the diffusion of CO_2 through the oceanic deep layers proceeds only very slowly. The second-right image in Figure 14 shows how long it takes for a (fictive) CO_2 pulse to be buffered by the global ocean (equivalent to a fictive +5%/a growth in fossil CO_2 emissions – which by the way leads even to an early exhaustion of fossil reserves).

In the view of this image (and its stacked equivalent in the rightmost position of Figure 14) it becomes plausible to speak about a century for the buffering effect time constant of the ocean. In other words: for the deep ocean, not only the present-day CO_2 concentration value is relevant but also the values of the past decades to century. This means: the global carbon system and especially the ocean has a "memory".

The operation of the ocean subprogram is crucial to the final result because the ocean is the main recipient of CO_2 in the global cycle over long periods of time, such as a century. This can be clearly seen from Figure 14 overall.

3. Generating Results

3.1. Modeling Biomass Fuels

One of the two main features of the CEBM (as different from usual biosphere models) is the inclusion of the possibility of using biomass for energy. To achieve this, the equations for carbon flows in the biosphere had to be changed in order to be able to model the growth and extraction of

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biomass fuels. These fuels are then to replace fossil fuels, taking into account the different calorific value (but not the different efficiency of technological combustion).

The model consideration of the energetic use of biomass should, on the one hand, do justice to realistic processes, but on the other hand should also correspond to the unavoidable prerequisite for sustainable biomass use. This required *sustainability* means that natural resources are used in such a way that subsequent generations have the same options for use e.g. [43]. For the special case of using biomass for energy, this means in particular that the existing plant mass should not be reduced during cultivation, but only the annual increase is used to generate energy. A definition of further criteria for sustainability can be found in [82], which also contains a definition of sustainability using a system-dynamics way of thinking.

This prerequisite for sustainability, which has been unwaveringly specified from the beginning of the modelling work, is represented in the CEBM as follows: The flow leaving the "phytomass" reservoir is called litter production (see at right in Figure 1, or in Figure 15, with the biomass-fuels-related additions in red). As already mentioned above, its size in stable equilibrium is identical to the net primary productivity. Regardless of whether the biomass fuels are harvested annually or at longer intervals, the long-term average of the biomass removed must be the same as that amount which grows annually, as is the case in classic forestry, for example. The flow "litter production" is now redirected: it no longer flows into the litter compartment, but forms the flow "*biomass fuel production*" (BMFP). The plant material is taken from the ecosystem via this flow and is to be used as fuel by the energy industry. In order to model the conditions as realistically as possible, it was assumed that 90% of the woody plant material, but not the herbaceous plant material, are used as fuel. The remaining material flows into the inventory waste as usual. In short, the energy industry harvests the wood that grows annually on the various areas in order to use it for combustion.

Table 1. The list of CEBM model variables, issued yearly as a global sum. For their modeling context, see Figure 1 (at right) or (for a larger image) also Figure 15. Data source: as in Figure 2.

Variable	*Unit*	*Designation*
ALZERO	Gt C	Global inventory decline at the beginning of the year
ALNEW	Gt C	Global reservoir of inventory waste at the end of the year
CO2	ppm vol	CO_2 concentration in the atmosphere
ASFCO	Gt C	Fossil emissions accumulated over the years
ASPHYTE	Gt C	Global phytomass
ASNPP	Gt/a C	Global net primary productivity
ASLP	Gt/a C	Global inventory waste production (litter production)
ASLD	Gt/a C	Globally decomposed inventory waste (litter depletion)
ASM	Gt C	Accumulated increase in the oceanic mixed layer since 1860
ASD	Gt C	Accumulated increase in the oceanic depth layer since 1860
ASMD	Gt C	Accumulated increase in the total ocean since 1860
SPVTO	Gt C	Global natural phytomass
SPATO	Gt C	Global agricultural phytomass
SNPV	Gt/a C	Global production of natural phytomass
SNPA	Gt/a C	Global production of agricultural phytomass
SDPHYT	Gt/a C	Globally cleared phytomass
TOTPH	Gt C	Emissions from cleared phytomass accumulated over the years since 1860
ASOC	Gt C	Global reservoir of soil organic carbon at the beginning of the year
ASOCN	Gt C	Global reservoir of soil organic carbon at the end of the year
ASOCD	Gt/a C	Globally depleted soil carbon

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ABURNT	Gt/a C	Global total of cleared biomass
ACSUM	Gt/a C	Global balance of the atmosphere → biosphere flow
AFCO	Gt/a C	Annual fossil CO_2 emissions
BSNP_	Gt/a C	Global production of phytomass for energy use
BSPTO	Gt C	Globally existing phytomass for energetic utilization
BACO	Gt/a C	Annual CO_2 emissions from biomass
RASFCO	Gt C	Remaining fossil deposit
CO2Gt	Gt C	CO_2 in the atmosphere in Gt

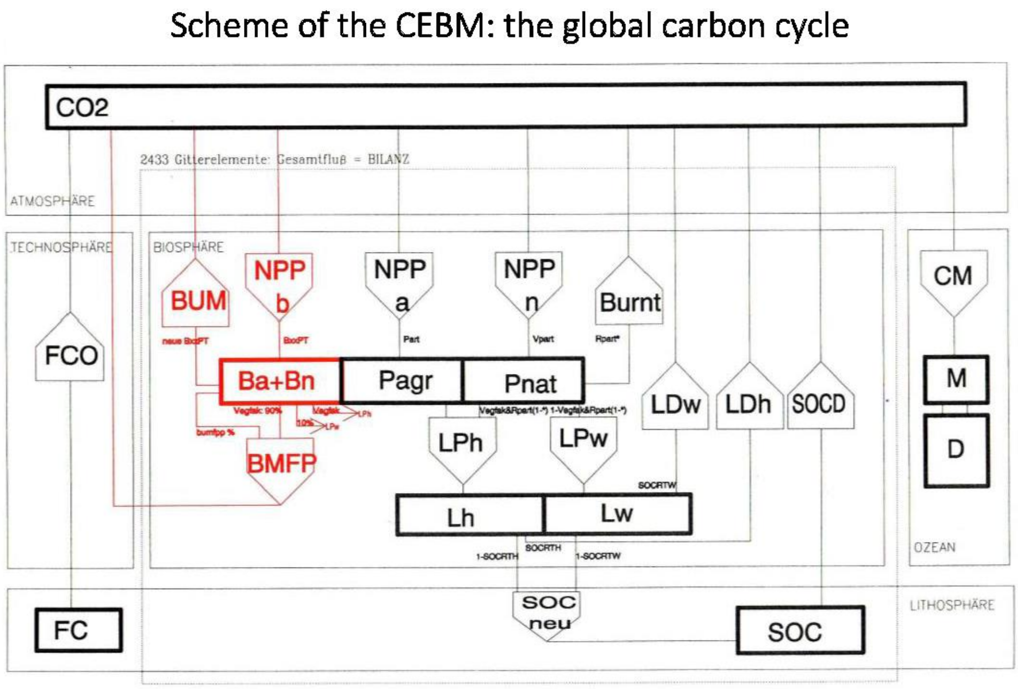

Figure 15. The structure of the global carbon reservoirs and flows in the CEBM. Data source: as in Figure 2.

As was already shown in the first test runs after implementation of the energetic usage of biomass, somewhat unexpectedly, the following amount of plant carbon represents a significant amount that must be closely monitored in order not to violate the balance equations: the large amount of plant material from the preceding mode of vegetation on those areas that are to be used (dedicated) for energy production. This amount of carbon is labeled “BUM” (standing biomass on the re-dedicated areas, “Biomasse-Umwidmung” in German) in the flow chart in Figure 15. In terms of program technology, it was planned that these quantities of plant material could either be partially or completely utilized for energy purposes (i.e., burnt in a combustion facility) or could be emitted directly into the atmosphere (i.e., burnt in the sense of blunt deforestation by fire). The control variable for steering the carbon flow "BUM" is called "bumfpp", as is also mentioned in Chapter 3.2.1 of the [83] annual report. In practice, a biomass energy industry will of course try to avoid these undesirable emissions as much as possible.

The exact results of this part of the program can be found in [41,45] and in the following sections.

3.2. Modeling the Processes Associated with Deforestation

The influence of the deforestation processes themselves on the CO_2 concentration has already been mentioned in more detail previously (see Chapter 3.1.2 in the 1991 annual report at [83], and in [45]. In the present section it remains to be described how big the impact on the atmospheric CO_2

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concentration will be under the CEBM's assumption that 50% of the herbaceous and 30% of the woody cleared plant material is immediately burnt and emitted. For this purpose, two test runs were carried out with the following extreme assumptions, each of which were opposite: one time, the entire (herbaceous and woody) plant mass should be emitted immediately, another time, nothing at all should be emitted immediately, but 100% should follow the usual degradation path via litter and soil carbon. Figure 16 shows that such model variations (i.e., assumptions regarding the exact procedures after deforestation) ultimately have a very small influence on the final result of the atmospheric CO_2 concentration.

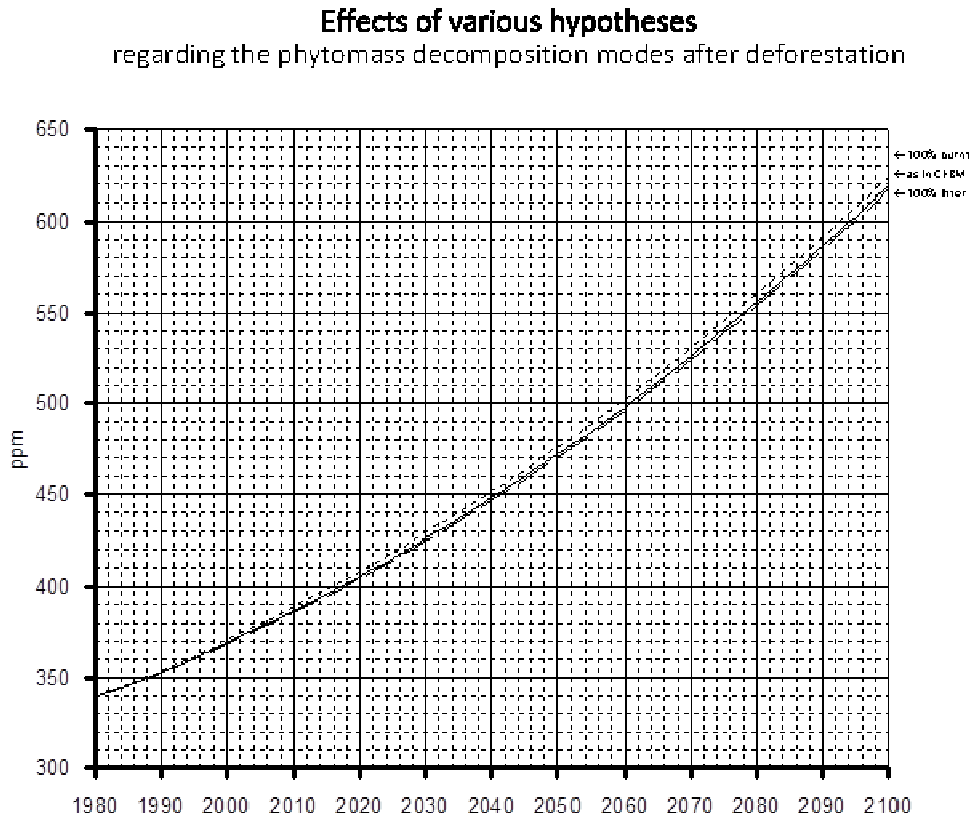

Figure 16. Sensitivity study regarding the type of modeling of clearing: three test runs. Data source: CEBM.

3.3. Where Does Emitted CO_2 Ultimately Go?

For an initial rough estimate of the complex dynamics and time behavior of the global carbon cycle system, one can consider in which compartment the emitted amounts of CO_2 will be ultimately deposited. The pie charts of Figure 17 and also Figure 14 at right provide information about this question: When considering one single given year (Figure 17 at left), CO_2 emitted from fossil or deforestation sources remains (i) in the atmosphere and in almost equal proportions (depending on the reference period considered) it is absorbed (ii) by the ocean through the mechanism of diffusion and (iii) in the biomass through the mechanism of the fertilizer effect. However, when considering a century, a more precise specification of the various carbon repositories is possible, but difficult because of the Earth's constantly flowing carbon streams. In this sense, Figure 17 (at right) quantifies that slightly more than half of the emitted carbon dioxide geos into the atmosphere while almost the other half goes into the ocean – a long-term distribution well in line with Figure 14 at right.

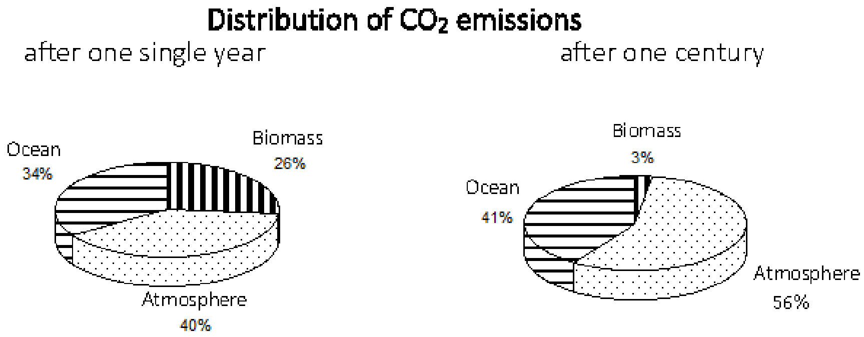

Figure 17. Distribution of CO_2 emissions across three compartments for different time periods, as a result of homeostatic equilibrium between global carbon flows and pools: at left: after one year; at right: after one century. Data source: CEBM.

In a given single year (Figure 17 at left), the CO_2 absorption into the plant cover through the fertilization effect is counteracted by global deforestation activity. The clearing processes, in turn, comprises firstly a spontaneous emission pulse due to combustion and secondly a flat emission process lasting several decades due to the rotting of dead plant matter. The ocean, for its part, has a CO_2 absorption characteristic that absorbs a CO_2 pulse (that suddenly occurs in the atmosphere, just to show the effects by this hypothesis) only over several decades. For all of these reasons, as well as because of the different time constants of the individual carbon fluxes in the biosphere, it is difficult to accurately identify (diagnostically) the emissions of a single year as an increase in the various carbon reservoirs. That's why the two diagrams in Figure 17 at left and at right differ so considerably from each other. Rather, the global carbon cycle represents a dynamic system that is constantly in flux – and this is an important structural message understood when contemplating the various CEBM model runs presented to date.

3.4. Results Regarding Carbon Neutrality of Biomass Fuels

After the preceding sensitivity studies that served to analyze the behavior of the CEBM when selecting diverse input parameter, one important set of scenarios is undertaken which picture (i) energy usage from biomass versus (ii) energy usage from completely carbon-free energy sources such as solar and wind. Figure 18 displays (a) the business-as-usual scenario (at the top) and (b) the base-case scenario (second from above – and the message of this comparison a-b is that diminishing the annual growth rate of energy demand will decisively lower atmospheric CO_2 concentration. Furthermore, starting out from the mentioned base-case scenario's energy demand, the (c) biomass scenario uses almost the maximum of the world's theoretical potential for biomass energy growth – covering gradually all available areas until the year 2100 by energy crops or energy forest. Next, (d) the low emission scenario assumes the same annual global energy demand as the two preceding ones but covers it with truly carbon-neutral energies such as solar and wind. And, still below (e) a global reduction target is visible. Overall, the comparison of lines c and d signifies that biomass strategies lower the atmospheric CO_2 concentration only halfway but not fully [41,45]. Hence, biomass fuels can be seen as "half as carbon neutral" as widely assumed on a quick theoretical level.

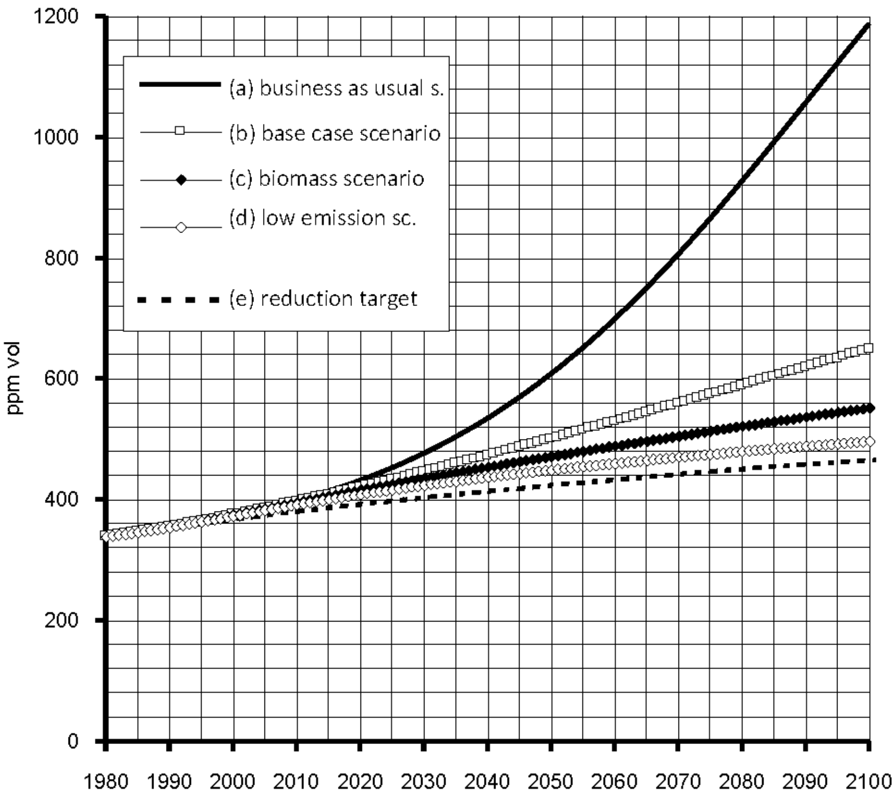

Figure 18. Comparison of atmospheric CO_2 concentration in different scenarios as a result of the CEBM.

3.5. On the Degree of C-Neutrality of Biomass

The above result can be explained as follows: According to the results of the CEBM, the removal of plant material from an ecological system over decades will deplete the (litter pool and more strikingly, because of its long-term nature) the pool of carbon in the soil (Figure 15, item SOC). This depletion of soil organic carbon becomes noticeable after decades and represents net carbon dioxide being emitted ultimately into the planetary atmosphere, just as did CO_2 after forest clearing, forest burning and subsequent long-term degradation of stems, twigs and leaves in a deforested forest: these emissions will be dispersed in the planetary atmosphere and ultimately half of it into the ocean (as already was shown in Figure 17 at right). Looking quantitatively at these systemic net CO_2 emissions (emerging from the organic soil layers) shows that approximately half of the initially avoided (fossil, energy-related) emissions emerge as biosphere-related emission – as a result of the interlinked carbon fluxed. Therefore, systematically, the cultivation and extraction of bioenergy engenders half of the avoided emissions through the "back door" of soil depletion [23].

On the level of envisaged carbon compartments, the soil carbon quantitatively stems from the activity of microbes that (as usual) decomposed dead plant matter. The flux from the SOC reservoir (namely SOCD, see Figure 15, modelled according to the formulae visualized in Figure 7) stays identical as before biofuel extraction (because microbes "do not know" whether new litter, LD, is flowing into the compartment SOC or not). Consequently, SOC decreases by the amount that corresponds to this same litter which is no more produced after large-scale extraction of biofuels from those areas. Thus, C can no longer, as was usual under natural circumstances, flow along the path "litter → SOC" (see Figure 15).

Therefore, any strategy of planet-wide biofuel production, extraction, and usage means a vast redirection of planet-wide carbon fluxes. Furthermore, such human action distorts an existing dynamic equilibrium of stable flows and counterflows, namely the natural carbon planetary carbon cycle. These fluxes of C are instead used by humans to generate energy by combustion and are (as the model results tell) therefore no more disposable for sufficient humus formation by natural procedures in the pertinent soil layers.

It may admittedly be that the CEBM's modeling results are not exactly accurate in terms of numbers, but given the current knowledge of the C cycle, it remains true undisputedly that an impoverishment within the soil compartment actually takes place. The extent of this depletion is most likely remarkable and meaningful in the long term, even if it may depend on the locally prevailing structure of soil horizons.

It can be recalled here that the approach of scenario-writing for the CEBM was to assume an (even thoroughly unrealistic) maximum worldwide usage of annually grown woody plant matter for its direct combustion, regardless of its practical feasibility and ethical appropriateness. Under the impression of the above-mentioned effects of biospheric CO_2 net emissions and soil depletion, one might wish to resort to just diminishing the amount of area dedicated for growing biomass for combustion, and to undertake modified strategies on a smaller scale. Although such scenarios have much less impact on the Earth's ecosystem, they (quite expectably) then offer only a minimal desired effect to curbing the greenhouse effect [41].

3.6. Comparison of the Mitigation Potential of the Different Scenarios

As far as the net mitigation of the greenhouse effect, i.e., the carbon dioxide concentration in the atmosphere (see Figure 18) in the various scenarios is concerned, we see that moving from the baseline to the biomass timeline equates a reduction of CO_2 emissions by only 0.5%, as summarized in Table 2. In 2100, the atmospheric CO_2 saving due to switching from the trend to the base scenario (i.e., energy consumption is reduced by two percentage points) amounts to some −550 ppm (Figure 18). The achievement through the theoretical maximum of universal energy use of biomass amounts to (only) −150 ppm (Figure 18). As a comparison, when viewing a climate-friendly path, a reduction of around −740 ppm is required. Thus, any *prioritization of measures* against the greenhouse effect must be carried out with the strikingly different magnitudes above.

To put it clearly, global maximal energy use of biofuels only produces 100 ppm. Thus, a global reduction in energy demand in inevitable.

Table 2. Comparison of the size of the CO_2 reduction that can be achieved by the year 2100, according to the CEBM calculations, as described by the model runs in Figure 18.

Scenario	**Atmospheric CO_2 content in the year 2100**	***CO_2 reduction compared to the trend case for 2100***
Trend = business as usual (+3%/a increase in emissions due to the increase in energy demand)	approx. 1200	-
global maximum biomass use (in trend scenario: +3%/a)	approx. 1000	*approx. -150*
Reducing the increase in emissions or energy demand from +3% to +1% (base scenario)	approx. 650	*approx. -550*
Combination of both methods (biomass scenario)	approx. 550	*approx. -650*
Reduction target (-1%/a)	approx. 450	*approx. -750*

This result of the model, namely that the **priority** is to *reduce the rate of increase in energy consumption*, is also in agreement with a large part of the literature such as [84–133], as thoroughly discussed in [41], p. 21-25.

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4. Conclusions

The intention of this study was also to provide a decision-making aid for energy planning on the socio-political and practical levels. For this reason, the following will be used to derive from the results of the work how the energy policy of an industrialized country should act. As an application example, we could see how the earlier energy policy of an industrialized country (such as Austria) met its existing goals of meeting demand (demand reduction), economic efficiency (security of supply), environmental compatibility and social compatibility (acceptance) and at the same time fulfilled some obligations in the face of well-founded concerns about the greenhouse effect – even if recent success is visibly more modest.

It follows also that an integrated package of measures is preferable to an individual measure not only in order to achieve equal success in the many sub-sectors and market niches of the energy industry, but also because of the staggered timing of the actual entry into force of the measures taken. In particular, in order to combat the increase in atmospheric CO_2 concentration, a package of changes is appropriate that can be implemented immediately and also can take advantage of the various economic and social effects and feedbacks-based self-reinforcing effects. The latter dynamics fall more into the structural and not purely technical area. Implementing the first (i.e., short-term) group of measures alone would have a certain short-term effect, but this would not be sufficient to achieve the overall goal. The implementation of the second (i.e., long-term) group of measures alone would have enough impact in the medium term, but valuable time would pass before they were actually implemented.

It is in the nature of things (and complies with a systems-dynamics approach, see [134,135] that short-term effective measures are more likely to be managed within the *technical* domain, while longer-term measures have to come from the *economic, political, behavioral and attitudinal* domains and therefore challenge people themselves in their behavior.

The *effectiveness of biomass as an energy source* in reducing atmospheric CO_2 concentrations was presented in detail in Figure 18 and Table 2. Exploiting even the theoretical potential for energetic biomass use across the globe will result in a concentration reduction of (only!) around 150 ppm in 2100 (amounting to the difference between base scenario and biomass scenario). Based on the trend scenario for global energy consumption, this is a marginal improvement in the greenhouse problem. Intensive global energy use of biomass *without* appropriate accompanying measures is therefore clearly not effective.

Moreover, it can be assumed that in practice the theoretical biomass energy potential cannot be fully exploited due to technical, economic and ecological limitations.

It can be deduced from the scenarios described that intensive efforts to reduce global energy consumption growth are an absolutely necessary prerequisite in order to ensure any significant success in the additional efforts to use biomass for energy worldwide or to implement other socially and ecologically compatible energy sources. This structure of the problem clearly results in a series of priorities for reducing the atmospheric CO_2 concentration: The most important measure (because representing the most effective measure), is the reduction of global energy consumption growth and the implementation of carbon-free energy systems based on solar energy to cover the energy demand remaining after demand has been reduced. Only if this will have happened, the introduction of global energy use of biomass (whereby the principle of sustainability must of course be maintained) would contribute to a significant approaching (not yet necessarily achievement!) to a climate-friendly reduction target.

These prioritizations are the result of the project in question and are logically and verifiably derived from the calculation results of the "Combined Energy and Biosphere Model" CEBM.

The project showed that the potential of fossil energy sources and biomass energy sources most likely has the maximums shown. This leads to the requirement to exploit other potential savings, especially reduction of energy demand and efficiency gains. Compared to the use of C-free (or any) energy sources, the advantage of reducing energy requirements is that no material flow of any kind has to be set in motion, with the help of which energy can be provided. It goes without saying that when selecting from the "non-carbon" group, only environmentally and socially compatible energy sources may be used, which already excludes nuclear energy [136].

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