Qualitative model of the long-term carbon cycle: the rise of the vascular plant during the Paleozoic period and its dramatic effect on our atmosphere

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Abstract

By essence qualitative modelling is of great interest for education in science as mentioned in many papers. In line with this statement modelling the processes that ought to be taught to students, such as the ones involved in the large biochemical cycles, is essential. This paper presents a set of four models to support both the modelling of the long-term carbon cycle and the explanation of a critical event in the history of our planet, namely the large drop of the atmospheric CO2 during the second part of the Paleozoic period (450-300 million years ago). The main processes are captured in a library of model fragments. Different clustering of model fragments allows for building qualitative models with different scope. In collaboration with domain experts this paper presents the essential processes to generate a consistent explanation of the phenomenon.

1 Introduction

Across science domains, science education addresses three topics: (1) How the scientific endeavour works (what do scientists do, and how does that lead to learning?), (2) causal theories of phenomena (what happens, when does it happen, what affects it, and what does it affect? [7], and (3) domain-specific facts (names, definitions, etc.). Of these, most time in the science class-room focuses on the second category. While student-active learning and inquiry-based instructional strategies have been shown to improve learning and knowledge retention, most introductory science education (including teaching of causal theories) relies on "'transmission-of-information' lectures and 'cookbook' laboratory exercises" [12]. Teaching causal theories using student-active or inquiry-based approaches presents challenges to educators. Most causal theories involve multiple interacting objects and processes and are often represented in diagrams that represent the collective understanding based on hundreds of studies on various components of the system (see Fig. 1 for an example of such a diagram). These diagrams are effective at representing the complexity of the system, but do not engage students in active-learning. Additionally, as static representations, they limit inquiry-based approaches like exploration of if-then scenarios involving indirect effects and multiple possible outcomes.

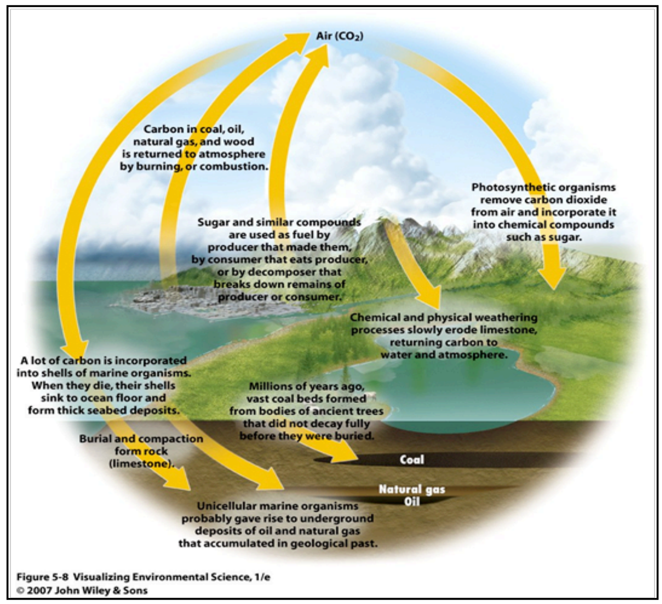

Figure 1. Example of representing causality in the carbon cycle (From [1], an introductory environmental science textbook aimed at non-science majors).

Qualitative reasoning and modelling (QRM) is an approach based on explicit representations of causality among entities in a system that allows dynamic simulation of system behaviour [8]. The QRM platform Garp3 [11] represents structural and causal relations explaining a system and its behaviour (dynamics) in a graphical form that students find easy to understand [13]. More in general, QRM has been shown to effectively teach domain-specific knowledge and causality in a variety of science and non-science domains [7].

1.1 Qualitative reasoning

A strong feature of qualitative reasoning is the ability to capture the conceptual knowledge about a phenomenon. Garp3 [11] provides a workbench to build qualitative models that also provides tools for simulating and inspecting the results. The ontology and the formalism implemented in Garp3 derive from key approaches to qualitative reasoning [5].

A Garp3 model involves several types of ingredients. *Entities* are the structural elements endogenous to the system. They are declared in Garp3 by using a subtype hierarchy graph. *Agents* represent the exogenous structural elements. Entities and agents can be connected using structural relations called *Configurations*. *Quantities* are the properties of *Entities* or *Agents*. *Quantities* are characterized by the couple <*magnitude, derivative*>. The former represents the actual value of the quantity, the latter the direction of change. The domain of value of a quantity is called a Quantity Space (QS), it is a finite and discrete set of symbols. QS is an abstraction or a mapping of a continuous numerical scale consisting in a succession of points (also called landmarks) and intervals. The derivatives have systematically the same quantity space, {*Min, Zero, Plus*}.

The key cause-effect relations are of two types: direct influence (I+; I−) and qualitative proportionality (P+; P−). The former represents the cause of the changes, whereas the latter represents the propagation of these changes. The causal relations are used to compute the value of the derivatives during the simulation. The workbench allows the use of constraints as value correspondences or inequalities $\{<, \leq, =, \geq, >\}$ as well as two arithmetic operations, + and -.

Key ingredients of qualitative models in Garp3 are *Scenarios*, they specify the state of the system at the start of a simulation, and *Model fragments* (MFs), which capture chunks of knowledge. During a simulation, the reasoning engine calls the MFs to determine the current state of the system and the possible transitions. The end result is a state-graph representing the behaviour of the system along time. Different views are available to inspect the results such as the value history diagrams [6].

1.2 The long-term carbon cycle

The long-term carbon cycle refers to the flow of carbon through the atmosphere, lithosphere, and oceans over millions of years, in contrast to the short-term carbon cycle, which operates over the course of minutes, days or years, mainly between the atmosphere, hydrosphere, and living organisms [3]. The long-term carbon cycle is relevant to Geosciences because of its relationship with climate, which is a major influence on Earth's surface processes. Additionally, the long-term carbon cycle is intimately related to macro-evolution of land plants and these have had, in turn, dramatic effects on the carbon cycle itself. Furthermore, development of models for aiding learning of the long-term carbon cycle will provide a basis for future development of models aimed at learning of the short-term carbon cycle.

The current state of knowledge about the long-term carbon cycle is embedded in the Geocarb III model, [4], in particular the evolution of the concentration of CO2 over time (Fig. 2). A complex numerical model such as Geocarb III cannot be taught easily to students. Moreover the results generated by Geocarb are estimates with large ranges of error (50% for the concentration of CO2), due to the lack of quantitative data for these periods of time.

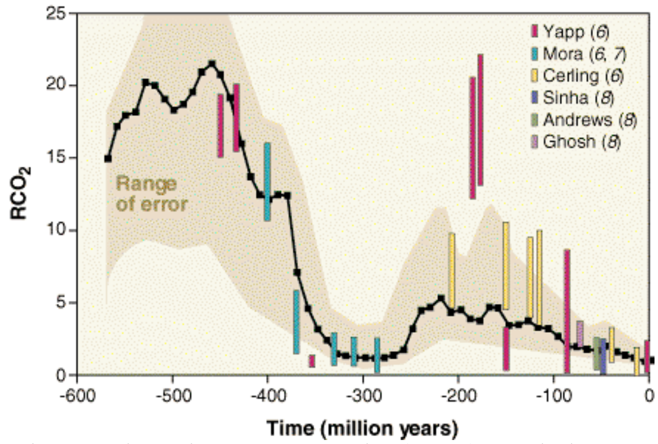

Figure 2. Change in CO2 concentration (RCO2) over the last 600 million years, as estimated by the GEOCARBII model (from [2]).

To explain the feedbacks and the processes at stake, domain researchers use instead traditional box models and cause-effect diagrams, or "systems analysis models", which Berner promoted to complement the more familiar box models [3]. Though these systems analysis models represent more explicitly the causal relationships than do box models, which emphasize flows, they remain static representations of dynamic processes. In contrast, Qualitative Reasoning (QR) models better represent causal and structural domain knowledge, and generate dynamic simulations of the evolution of quantities over time. Hence, learners can explore the consequences of the causal and structural relationships on system behaviour.

In his system dynamics models of the long-term carbon cycle, Berner represented two entities, or subsystems: the organic (living) and inorganic (non-living) components of the system. In this paper, we describe the main processes related to these two entities.

2 QR model of the effect of the evolution of plants on the long-term carbon cycle

2.1 Model goals

The goals of our set of QR models are to represent an explanation of the impact of plant macro-evolution on the long-term carbon cycle. The focal quantity is the change in carbon dioxide levels in the atmosphere over time, as depicted in Fig. 2. Thus, the objective is to reproduce the kinetic depicted in Fig. 2 by incorporating the processes of the long-term carbon cycle. In particular, we focus on the period from 450 to 300 million years ago that captures the dramatic effects that the evolution of the early non-vascular and seedless vascular plants hand on atmospheric carbon dioxide levels.

2.2 Model implementation

The models are implemented using Garp3 workbench. We modelled several processes described in the previous section separately, and then combined them into a global model. Taking this approach we developed four models, three self-contained QR models that each provide insight into specific processes, notably silicate weathering, burial of organic matter, adaptation of the plants to life on land, and one global model that integrates these processes.

2.2.1 Entities and overview of the system

The system has four main entities, *Atmosphere*, *Sedimentary rocks*, *Silicate rocks*, and *Land plants,* and their respective subtypes:

Entity: *Atmosphere*
Subtype: *Composition*
Description: the atmosphere has a gas composition with carbon dioxide that exchanges carbon with the other compartments of the system.

Entity: *Sedimentary rocks*
Subtype: *Carbonate rocks*, *Organic-rich rocks*
Description: sedimentary rocks are rocks formed by sedimentation. We discern two types: (*i*) carbonate rocks, such as limestone, are formed by deposition of carbonate particles, and (*ii*) the organic-rich sedimentary rocks, such as coal, resulting from the burial of organic matter.

Entity: *Silicate rocks*
Description: rocks with calcium and magnesium silicate minerals.

Entity: *Land plants*
Description: land plants developed specific traits to live on land. They produce biomass via photosynthesis using the carbon dioxide in the air.

Entity: *Carbon reservoir*
Description: compartments of the carbon cycle can be seen as different carbon reservoirs.

The entity called *Carbon reservoir* is used to control the total amount of carbon in the system. *Silicate rocks* is an entity that is partly involved in the system. We are not interested in the amount of silicate rocks, which is an exogenous quantity, but the silicate weathering process plays an important role in the phenomenon and is a part of the system.

The relations between the entities of the system (*configurations* in Garp3) are shown in Fig. 3. The *evolution process* of land plants is a modelling assumption used to generate the complete explanation of the phenomenon.

The boundary of the system is reflected by the details in Fig. 3. We kept the system minimal, leaving aside processes such as plate tectonics (e.g. subduction), volcanism, metamorphism and diagenesis that are also a part of the long-term carbon cycle [3].

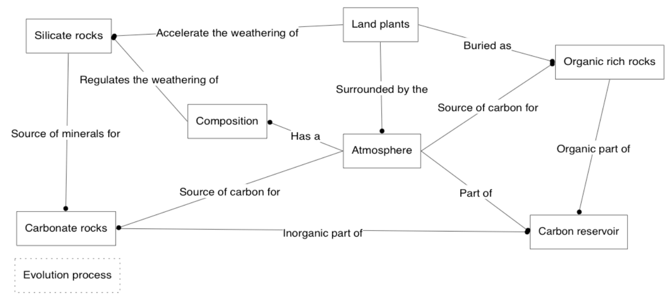

Figure 3. Overview of the system with Entities and Configurations.

2.3 Atmosphere and climate

The atmosphere composition is captured in a static Model Fragment (MF) (left side Fig. 6.). The entity *Composition* has two quantities, *Amount of carbon dioxide* and *Rainfall*. There is a positive proportionality between *Amount of carbon dioxide* and *Rainfall* to represent positive relations between the concentration of CO2 in the air and the amount of precipitation. In our system the amount of precipitation is important because of its influence on the silicate weathering process [3]. Note that the focus of the model is not on the Earth's climate, so the causal chain representing the climate is minimal, thus the air temperature is not included in the system.

In order to visualize the drop of CO2, we use the {*Low, Medium, High*} quantity space for *Amount of carbon dioxide*. The values of the CO2's QS must be interpreted relatively to the current level of CO2 in the air, thus the *High* value is the level of CO2 before the radiation of the vascular plants (prior to and around 400 myr, Fig. 2), that is more than 10 times the current value, the *Medium* and *Low* values represents the level of CO2 after 400 myr (Fig. 2).

2.4 Control of the amount of carbon in the system

The system should respect the law of conservation of mass applied to the carbon element. The law of conservation is represented by a sum of the different reservoirs of carbon whose result is the total amount of carbon "in the world", which is constant. To implement this idea we define an entity called *Carbon reservoir* having a quantity *Total Carbon* whose value is constant (the QS has only one value). *Total Carbon* is the result of the sum of the carbon reservoirs of the system, thus the terms of the sum change with the scope of the model. For example the QR model of the inorganic subpart implements the following sum:

Total Carbon = Atmosphere(Amount of carbon dioxide) + Carbonate Rocks(Amount of carbon)

By connecting the 3 subparts in the global model, the distribution of carbon among the reservoirs is controlled by the following sum:

Total amount Carbon = Atmosphere (Amount of carbon dioxide) + Carbonate Rocks(Amount of carbon) + Organic rich Rocks (Amount of carbon)

To keep the sum simple we made the choice to leave aside the carbon stored in the land plant population when the sediments are a part of the system. In doing so we assume that the amount of carbon used in the land plants tissue is negligible compared to the amount locked up in the sediments during this period of time.

The quantity *Amount of carbon* has the same QS as *Amount of carbon dioxide*, i.e. {*Low, Medium, High*}. For the sum to act as an effective constraint we specify that the result of the sum of the *Medium* values of the carbon reservoirs' QS is equal to the value of *Total carbon*. Additional simplifying value correspondences can be stated between the respective QSs to reduce the space of solutions of the sum and then the size of the simulation.

2.5 Sedimentary rocks formation

The *Sedimentary rocks* entity has the quantities *Amount of carbon,* which can be viewed as a reservoir, *Deposition rate* and *Weathering rate* which represent respectively the rate of formation and the rate of loss of sediment rocks (Fig. 4).

Generally speaking the formation of sediment implies the deposition of sedimentary particles (*Deposition rate*). The weathering (*Weathering rate*) is an opposite process that is the breaking down of rocks, reducing the amount of sedimentary rocks. We define the quantity *Net deposition of carbon* as the difference between *Deposition rate* and *Weathering rate*. Its value can be positive or negative (QS: {*Min, Zero, Plus*}). There is a positive influence (I+) between *Net deposition rate* and *Amount of carbon.*

The Figure 4 represents the combination of the two MFs that implement the generic principle of the sedimentation process (one static MF and one process MF).

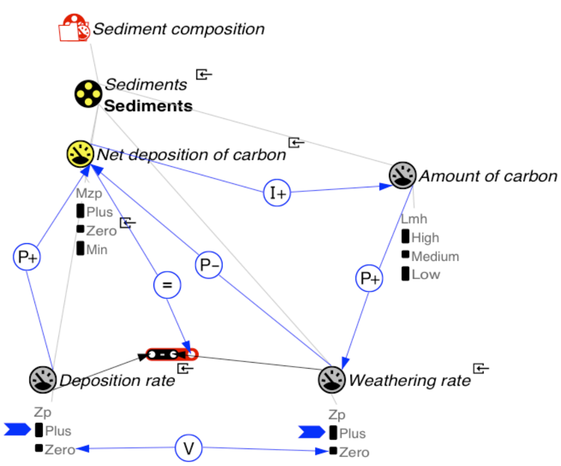

Figure 4. Sediment formation MFs

2.6 Formation of carbonate rocks

The formation of carbonate rocks constitutes a self-contained subpart of our system and is captured in a first model. This process is part of the inorganic long-term carbon cycle and of the silicate-carbonate subcycle [3] relating the silicate weathering to the formation of carbonate rocks. Incidentally it explains how a net formation of carbonate rocks results in a net removal of atmospheric CO2.

The formation of Carbonate minerals is predominantly found in marine environments and most is biologically mediated. The transfer of Calcium, Magnesium and Carbonate ions from land to oceans is not represented in the model as well as the role of the marine organisms in the sedimentation process.

2.6.1 Modelling the silicate weathering process

The MFs representing the sedimentation process (cf. section 2.5) are used as such in this subpart. The specificity of the formation of carbonate sediments is the relation with the weathering of silicates rocks (entity *Silicate rocks*) (Fig. 5). The whole process results in a net removing of carbon dioxide from the atmosphere (see Fig. 6).

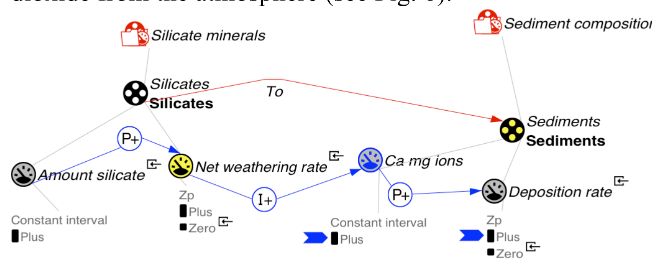

Figure 5. Silicate weathering and relation with carbonate sediments

The *Silicate rocks* entity has two quantities, *Amount of silicate* and *Net weathering rate* (Fig. 5). *Amount of silicate* is thought to be an exogenous quantity whose magnitude is constant over time. Strictly speaking *Net weathering rate* is the difference between the weathering and the formation of silicate rocks. However the formation of silicate rocks involved the metamorphism of carbonate rocks, which is out of the scope of the model, thus we consider only the net excess of silicate weathering. This is captured by a *Net weathering rate*, which can be positive or zero but never negative (QS: {*Zero, Plus*}). The weathering of rocks on land increases with the amount and the frequency of *Rainfall*, therefore *Rainfall* is positively related (P+) to *Net weathering rate* (Fig. 6).

The relations with the *Carbonate rocks* starts with the weathering of the silicate rocks. This releases dissolved Calcium and Magnesium ions to be transported by river systems into the oceans. So *Net weathering rate* has positive influence (I+) on *Ca and Mg ions* (Fig. 5). *Ca and Mg ions* are used by marine micro-organisms as carbonate minerals. These organisms live near the surface of the ocean, and following death they sink to the seafloor. Here they combine with millions of other micro-organisms and move from the biosphere into the geosphere in the form of Carbonate rocks deposits. This is captured by a positive proportionality (P+) from *Ca and Mg ions* to the sediments' *Deposition rate* (Fig. 5).

The *Net deposition of carbon* process represents a net uptake (I-) of Carbonate ions, which in turn has the net effect of removing the carbon from the CO2 in the air, (P+

from *Carbonate ions* to *Amount of carbon dioxide*) (Fig. 6). Since *Amount of carbon dioxide* and *Rainfall* are positive proportional, the whole process forms a negative feedback loop that explains the fact that the evolution of the climate damps the formation of carbonate rocks.

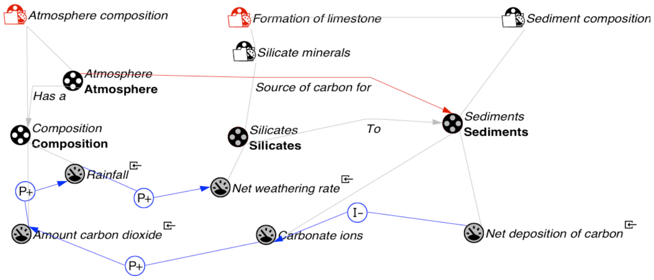

Figure 6. Relation between the formation of carbonate sediments and the climate.

The representation of the formation of *Carbonate rocks* in Fig. 5 and 6 is detailed because students have difficulties understanding this process. This representation stresses the difficult points spotted by the experts although, admittedly, a complete representation would imply even more dependencies

2.6.2 Scenario and simulation results

This first model has one scenario (Fig. 7) to assess the impact of a net excess of silicate weathering on the atmospheric CO2.

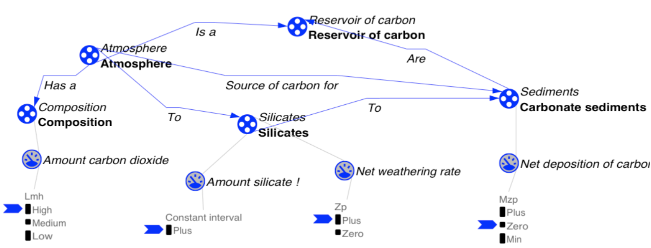

Figure 7. Net excess of silicate weathering scenario.

Net deposition of carbon is set to zero *Amount of silicate* is set to *steady*. The simulation generates a state-graph of 16 states, 1 initial state and 3 end states corresponding to the possible distributions of the carbon among the two carbon reservoirs of the model: *Amount of carbon dioxide* and *Amount of carbon* in *Carbonate rocks*. The pathways of the state-graph are variations of the same behaviour. As shown in Fig. 8 the excess of silicate weathering (state 1) brings about an increase of the formation of carbonate sediments and consequently a decrease of *Amount of carbon dioxide* [2→5→6→13→10]. *Rainfall* decreases as well damping down the silicate weathering process through the decrease of *Net weathering rate* of *Silicate rocks* which ends up stabilizing at zero from state 13. The stabilisation of *Net weathering rate* propagates to the *Net deposition of carbon* in *Carbonate rocks* after a few states (state 9).

Interestingly the pathway (Fig. 8) shows that *Net deposition of carbon* in *Carbonate rocks* does not necessarily respond instantaneously to the variation of *Net weathering rate* of *Silicate rocks*. In reality, it takes time for the weathering of carbonate sediments to balance out the deposition process. This time lag between the two processes is nicely conveyed by the simulation's results.

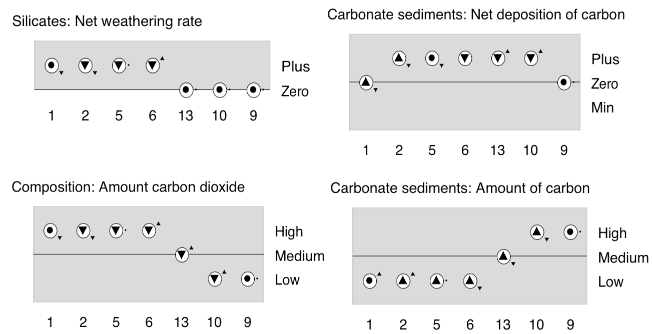

Figure 8. Value history showing the net silicate weathering excess.

2.7. Formation of organic-rich sediments

This subpart covers the formation of organic-rich sedimentary rocks from the land plants detritus. This process representing a significant part of the organic long-term carbon cycle, is captured in a specific QR model.

Formation of carbon-based detritus by plants provides the opportunity to remove carbon from the short term carbon cycle and move it into the long-term cycle. The burial of plant material, such as peat, tree trunks and other organic detritus, and the conversion of that material into organic-rich sedimentary rocks allows for the long-term sequestration of carbon.

2.7.1 Modelling the burial of organic matter

The plant growth MF is given Fig. 9. The QS of *Land plant biomass*, {*Small size, Full bryophyte, Large size, Max vascular plant*}, is meant to represent the distinctive states of the land plant population over the second part of the Paleozoic period. *Small size* and *Full Bryophyte* values describe the population of the early land plants (i.e. Bryophytes), they are small plants that colonized a limited area on land. The radiation of the vascular plants happens later, they are on average bigger and colonized a much larger area (values *Large size* and *Max vascular plant*). *Net primary production* represents the net result of photosynthetic uptake of CO2 and its conversion to plant biomass. This rate has no negative value, QS: {*Zero, Plus*}, because we consider only the spread of land plants; thus we assume that no visible decline of the land plant population happens during this period of time.

The sedimentation process is described in section 2.5. Here *Deposition rate* represents the burial rate of organic matter when associated to organic-rich sedimentary rocks. The relation between land plants and the burial of organic matter is the following: the more the *Land plant biomass,* the more carbon-based detritus are produced and then buried. This is captured by a positive proportionality (P+) from *Land plant biomass* to *Deposition rate*.

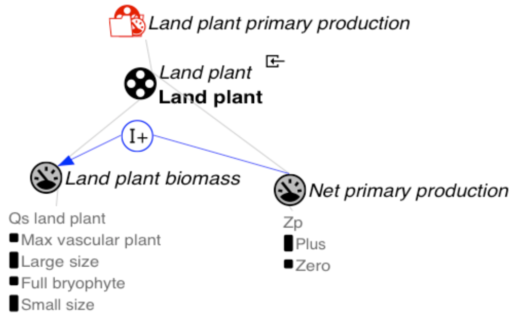

Figure 9. Pant growth process model fragment.

There is a negative influence (I-) from the *Net deposition of carbon* in organic-rich sediments towards *Amount of carbon dioxide* represents the fact the net burial of organic matter has a net effect of removing atmospheric carbon dioxide. Note that this negative influence represents the flow of carbon captured by plants through photosynthesis that is ultimately locked up for a long-term in organic-rich sedimentary rocks. Therefore in our context there is no direct influence between *Net primary production* and *Amount of carbon dioxide* when the burial of organic matter is involved.

2.7.2 Scenario and simulation results

This QR model has one scenario aiming at exploring the effect of a variation of *Net primary production* on the formation of organic-rich sedimentary rocks and ultimately on *Amount of carbon dioxide* in the atmosphere.

Net primary production is set as an exogenous quantity with a positive parabola pattern[1] and starts at zero. The values of the quantities of the sediment part are similar to the ones of the scenario Fig. 7.

The state-graph is rather large (in total 62 states, with 7 stable end states), because the QS of *Land plant biomass* is large and the evolution pattern of *Net primary production* is complex. The increase of *Net primary production* during the first half of the positive parabola brings about the increase of *Net deposition of carbon* as *Organic-rich rocks*, the result of the process is a net removing of CO2 represented by a decreased *Amount of carbon dioxide*. When *Net primary production* decreases and goes down to zero, this propagates to the *Net deposition of carbon* as buried organic matter, either instantaneously or after a time lag (that is after a few states in the simulation).

2.8 The adaptation of the plants to life on land

This subpart encompasses the processes that refer to the land plant population, namely the plant growth and the adaptation to life on land. The plant growth MF is described section 2.7.1. This section focuses on the adaptation process.

As a matter of fact over the last 500 million years, land plants have become increasingly adapted to life on a wider variety of terrestrial habitats, allowing them to expand all over the globe [2]. This adaptation has resulted in an increase of primary production of the plants as well as greater interactions with inorganic processes, notably rock weathering. The details about the adaptation of plants on land are captured in our third model.

2.8.1 Competition for space

As plants began to occupy all available habitats, the competition among plants for the available resources increased, exerting a negative pressure on the plant growth. This knowledge is captured in a static MF (Fig. 10) by the following chain of dependencies: *Available habitable area* is inversely proportional (P-) to *Competition,* which in turn is inversely proportional (P-) to *Net primary production.*

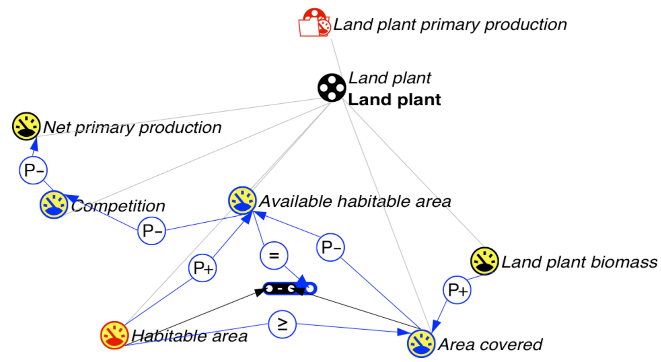

Figure 10. Competition for space model fragment.

Available habitable area is the difference between the *Habitable area* and the *Area covered. Habitable area* represents the area plants can colonize given the level of their physiological developments. *Area covered* is the area covered by the land plant population (captured with a P+ from *Land plant biomass* to *Area covered*). The plants cannot possibly cover more surface than *Habitable area*, this constraint is captured by the following inequality (see also Fig. 10): *Area covered* ≤ *Habitable area.*

The QS of *Habitable area*, {*Bryophyte, Max Bryophyte, Vascular plant, Max vascular plant*} reflects the extent of the land plants habitat according to the dominant kind of land plant. Bryophytes can cover a maximum area corresponding to the value *Max Bryophyte*, the development of vascular plants expands this area to a greater maximum threshold (namely *Max vascular plant*). The QS of *Area covered* is the same as the one of *Land plant biomass* (section 2.7.1), as a matter of fact a correspondence is set between the values of these two quantity spaces.

Combining this causal chain with the plant growth process (Fig. 9), we get a negative feedback loop that regulates the production of *Land plant biomass* through the effect of the *Competition* among the individuals. A value correspondence between the zero values of *Available habitable area* and *Net primary production* is a means to

[1] Positive parabola refers to a quantity starting at a certain value, increasing to its highest value and after that decreasing to its lowest value. See [9] for different exogenous quantity behaviours.

state that when there is no more available area to occupy *Land plant biomass* becomes stable.

2.8.2 Adaptation to life on land

The level of adaptation of the plants on land is represented by the quantity *Adaptation to life on land* (Fig. 11). The QS reflects important features of land plants that were selected and developed at that time: {*Bryophyte characteristics, Vascular tissue, Roots, True leaves*}. The QS respects roughly the apparition of new traits amid the land plant population.

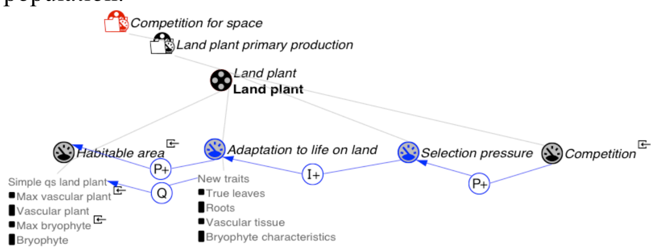

Figure 11. Adaptation to life on land model fragment.

We assume that the *Habitable area* increases along with *Adaptation to life on land* (P+ and Q-correspondences Fig. 11), meaning that the developments of physiological innovations during that period of time gave to the plants the opportunity to extend their habitable area. When most of the Earth surface can be covered by plants, the adaptations do not result anymore in a significant increase of the habitable area. Therefore when *Adaptation to life on land* reaches its maximum value (*True leaves*) we consider that the consequence of the adaptation is no more an increase of *Habitable area*, the P+ relation between these two quantities is then ruled out.

The *Competition* between the individuals contributes to the *Selection pressure* that in turn influences positively the level of adaptation by the selection of the most adapted individuals. This knowledge is captured by positive proportionality (P+) from *Competition* to *Selection pressure*, which in turn influences positively (I+) *Adaptation to life on land* (Fig. 11).

2.8.3 Scenario and simulation results

The model has three scenarios to test respectively the plant growth process, its regulation by the competition for space, and the adaptation to life on land. The former imposes to define *Net primary production* as an exogenous quantity with a positive parabola pattern, as for the organic subpart (section 2.7.2).

The first scenario generates four end states with stable values, *Land plant biomass* increases and can stabilize at any value of its QS.

With the second scenario *Habitable area* is set to a given magnitude and a *steady* pattern. As expected, *Land plant biomass* increases and stabilizes when *Available habitable area* = zero (*Habitable area = Area Covered)* because the spread of the land plants is no more possible (*Net primary production = zero)*. This scenario implements the negative feedback exerted by the *Competition* on *Land plant biomass*.

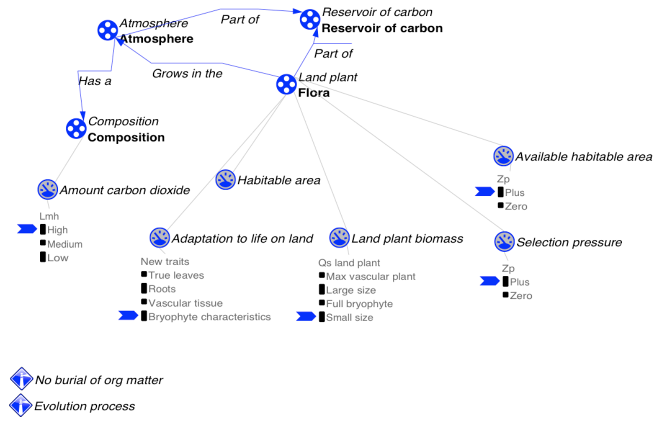

Figure 12. Adaptation to life on land scenario.

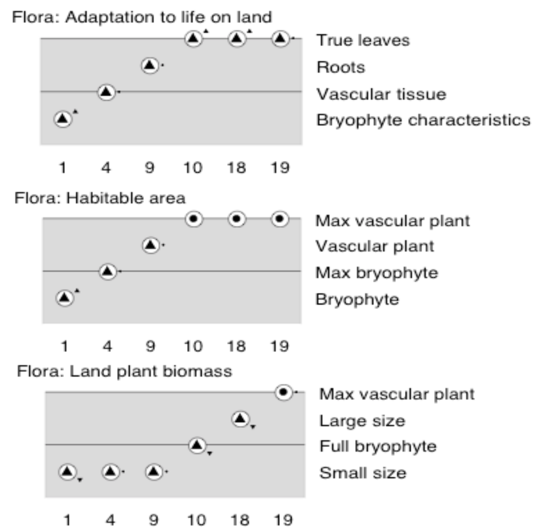

Figure 13. Adaptation to life on land value history graphs.

The last scenario extends the previous scenarios and needs no exogenous quantities (Fig. 12). The state-graph has 19 states, 3 initial states and 1 end state. There is one type of behaviour epitomized by the value-history graph (Fig. 13). *Adaptation to life on land* increases all along because the value of *Selection pressure* is always positive (not shown in Fig. 13). *Habitable area* follows, up to its maximum value (*Max vascular plant*) then stabilizes because the adaptation of plants results no more in an increase of *Habitable area* (from state 10 to 19). As long as *Available habitable area* is above zero, land plants can spread on land (increase of *Land plant biomass*), once *Habitable area* stabilizes land plants eventually cover completely the habitable area. When this occurs *Net primary production* becomes zero and *Land plant biomass* becomes stable (state 19).

The level of *Adaptation to life on land* acts as a constraint for the spread of the land plant population. For example the completion of the adaptation of the Bryophyte, namely when *Adaptation to life on land > Bryophyte* *characteristics*, is required before *Land plant biomass* might reach the value *Full Bryophyte*. This explains why the evolution of *Land plant biomass* follows the one of *Adaptation to life on land* with a time lag.

2.9 Modelling the effect of the rise of the vascular plants on atmospheric CO2

With the advent of vascular tissue and deep root systems, plants dramatically changed the biogeochemical weathering process on Earth [2]. The breakdown of the silicate rocks is accomplished through interactions between the biosphere and geosphere both physically and chemically.

2.9.1 Rooted plants and silicate weathering

The relation between land plants and silicate weathering is captured in the specific static MF "Roots' incidence on silicate weathering" (Fig. 14). Once land plants develop roots (*Adaptation to life on land = Roots ∨ True leaves*), the *Net weathering rate* of silicate rocks is positive proportional with *Land plant biomass* because the spread of rooted plants accelerates the weathering of silicate rocks [2].

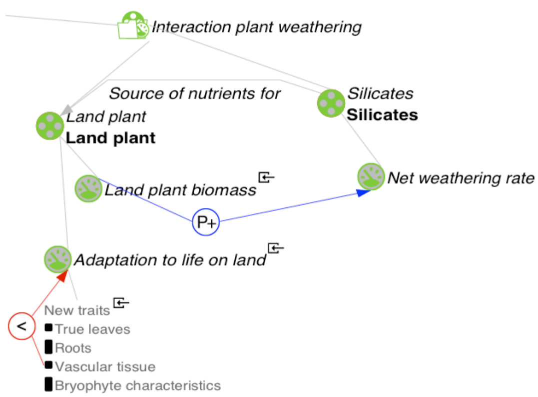

Figure 14. Rooted plants and silicate weathering model fragment.

However with this MF alone, the *Net weathering rate* of silicate rocks could increase even if *Land plant biomass* is almost stable. In such situation the feedback from the decreased *Rainfall* climate (section 2.6.1) should be predominant and the silicate weathering should be slowed down. To be sure that the system behaves this way we implement the following constraint in a conditional MF:

IF Adaptation to life on land = True leaves
THEN ∂(Net weathering rate) ≤ zero

2.9.2 Scenario and simulation results

The model has three scenarios: (1) to test the effect of the rise of land plants on the formation of carbonate sediments, (2) to test the effect of the rise of land plants on the formation of organic-rich rocks, and (3) to simulate the effect of the rise of the land plants on the atmospheric CO2 with the two types of sedimentation.

The two first scenarios give state-graphs of respectively 211 states with 3 end states, and 45 states with 2 end states. The state-graph of the last scenario has 944 states with 6 end states. All the end states represent a possible equilibrium of the system (respecting the sum that controls the distribution of carbon among the reservoirs). Two simulations are large because we purposely left the qualitative model largely unconstrained so to assess the underlying causal models.

The behaviour of the third scenario encompasses those of the first two. It is illustrated in the value-history graph (Fig. 15). The graph illustrates the timing of the different processes. The *Net primary production* increases first (state 1), followed, state 2, by the *Net deposition of carbon* in an organic-rich sedimentary rocks (net burial of organic matter). Once plants develop roots (*Adaptation to life on land = Roots*, state 10 to 16), the *Net weathering rate* of silicates rocks increases (state 10), followed by the *Net deposition of carbon* in carbonate sediments (state 13). The combined processes bring about eventually the significant drop of *Amount of carbon dioxide* (states 50, 74, 208) as the amount of carbon locked up in the sediments increases accordingly.

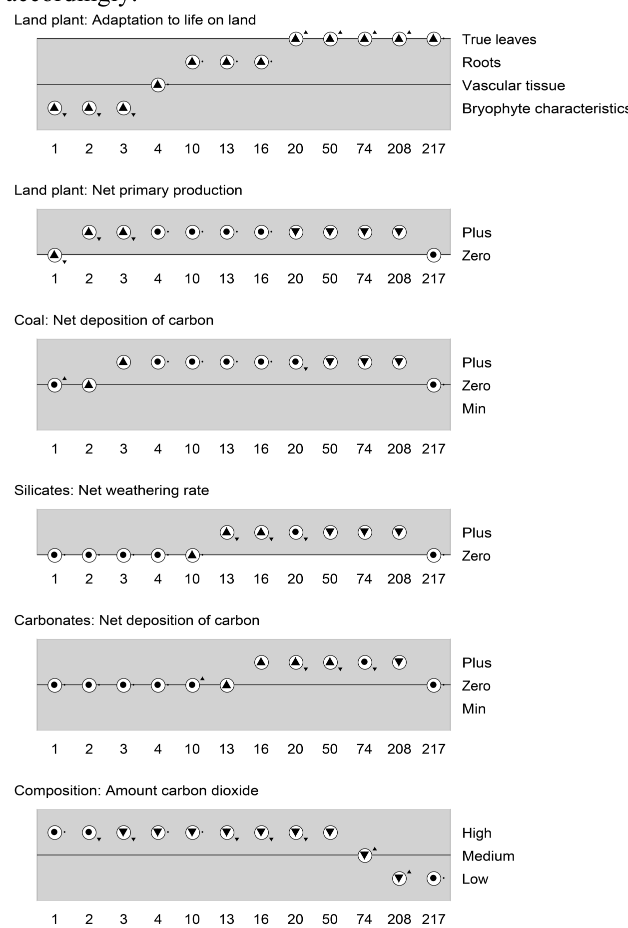

Figure 15. Effect of the rise of the land plants on atmospheric CO2

The size of the state-graph generated by the third scenario can be reduced drastically using constraints like value correspondences and inequalities, especially to frame the results of the sum of carbon reservoirs. For instance the graph Fig. 15, is generated with a version of the model with a value correspondence between the *Amount of carbon* in on one hand *Carbonate rocks* and, on the other hand, *Organic rich rocks*. This makes the state-graph smaller and easier to handle.

3 Discussion

Building a qualitative model as a support for teaching supposes to make choices to convey the important notions to learners and to answer the question "what is causing the changes". In building the present system we strived for a simple self-contained system (no forcing functions) so to be able to answer this question. This led us to extend vertically the causal chain, including the processes of the land plant subpart that were out of scope of the seminal article of Berner [2]; in return we left aside feedbacks that were mentioned in the article to limit the ambiguity of the model.

The large size of the state-graphs is a limitation for education. However in our case the great majority of the pathways of a given state-graph are instances of a single generic behaviour, meaning that selecting one pathway randomly is enough to observe the expected behaviour. The fact that Garp3 can automatically select the shortest pathway from a state also alleviates the difficulty.

4 Conclusion

We have successfully implemented the main processes related to the long-term carbon cycle into a set of QR models. Each of the three subsystem models provides realistic dynamics that show how each of these processes affect organic and inorganic components of Earth's systems. Furthermore, the global model that integrates all these processes realistically portrays the dynamics of the full numerical Geocarb model presented by Berner [2]. The results of the simulation (Fig. 15) show how the adaptation of plants to life on land results in an increased land plant biomass and in a reduction of the atmospheric carbon dioxide concentration as more and more carbon is locked up in carbonate sediments (via weathering and carbonate precipitation) or buried in carbon-rich materials that eventually form coal.

At around 400 million years ago the evolution of CO2 stabilizes (see Fig. 2), this reflects the fact that the early non-vascular plants' ability to further draw down CO2 is saturated. In reality, it took a few million years for the adaptation of vascular tissue to arise, which allowed plants to again start expanding over the globe and draw down CO2 from not only increased primary production, but also greatly enhanced weathering and precipitation of carbonate sediments in the oceans, after about 410 million years ago. Ideally, the model should also be able to capture this delay, with CO2 stabilizing at a value above low for a time before it again drops following evolution of vascular tissues and roots, but currently it does not. This is because the adaptation level of the land plant population does not react instantaneously to a positive selection pressure as assumed in the model. We are working on further improving the model details regarding the response of adaptation to competition.

In summary, the model described in this paper adequately incorporates the main processes highlighted by Berner [2], explaining how the rise of vascular plants shaped the long-term carbon cycle. We look forward to implementing learning modules in our undergraduate Geosciences and Biology courses that use the model to aid student learning of these complex processes.

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