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System Dynamics Modeling of the Impact of Economic Growth and Carbon Pricing on Greenhouse Gas Emissions in the Niger Delta

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Abstract: The Niger Delta in Nigeria is an area of high economic activity, especially in the oil and gas sector, which not only has been responsible for a considerable increase in the emissions of greenhouse gases but also has caused the degradation of the environment. It is thus a main challenge for the government to come up with policies that would make it possible for economic growth to continue while the environment is still protected. The current research presents a mathematical model that is based on system dynamics to analyze the interactions among the three forces of economic growth, carbon pricing policies, and greenhouse gas emissions in the Niger Delta region. The model combines the dynamics of macroeconomic growth, mechanisms of emissions production, and carbon pricing as a form of regulatory feedback control. A set of coupled nonlinear differential equations is created to describe the changes in output, emissions intensity, cumulative emissions, and carbon price dynamics over time. The fundamental qualitative characteristics of the model, like positivity, boundedness, equilibrium existence, and stability, are proven. A semi-analytical solution method that uses the Differential Transform Method (DTM) is applied to derive the dynamic solutions and policy implications that are approximated. The scenario analyses exhibit that putting in place a reasonable carbon price can lead to a situation where economic growth is no longer accompanied by emissions growth, thus making it possible for the environment to be sustainable in the long run without any major contraction in the economy. The findings give a numerical framework for the design of climate and environmental policies that are in line with the goal of sustainable development in the Niger Delta.

Keywords: System Dynamics, Economic Growth, Carbon Pricing, Greenhouse Gas Emissions, Niger Delta, Differential Transform Method

1. Introduction

The act of oil drilling, industrial activities, gas flaring, and the development of associated infrastructure have traditionally been major factors driving economic activities in the Niger Delta region. Being the most prolific oil-producing region in Nigeria, the Niger Delta has, for many years, significantly influenced national revenue and employment creation [1]. However, in return for its economic supremacy, it has brought in heavy burdens on the environmental and social spheres. Intensive and long-fallow fossil fuel extraction has excessively boosted greenhouse gas emissions, produced damage to land and water resources, biodiversity losses, and health risks from enveloping the region in a very delicate bundle environmentally, as well as exposing it to climate risks economically [2, 3].

In the context of the worldwide policy emphasis on lowering emissions from greenhouse gases, market-based instruments (like the idea of carbon taxes and other forms of emissions trading) have been moving to a better position; these instruments have become the central analytical mechanism for "costing out" the environmental impacts of economic activity. The market mechanisms themselves (such as carbon taxes and emissions trading schemes) will accord cleaner production and encourage the adoption of low-carbon technology on all those grounds where the use of certain technologies would be diminished with reductions in emissions but without the slightest hint of economic viability in the long run [4, 5]. They are not perfectly successful, though. Carbon pricing liberalization would be working in the developing economies that rely heavily on fossils, such as inorganic structures, low regulatory capacity, and deep industrial resistance. Poorly designed and implemented carbon pricing policies may lead to the unintended burdening of the economy [6, 7]. These perennial challenges are felt in the Niger Delta region, most obviously there, where petroleum-related activities tend to monopolize the whole economic system, and where regulation and environmental conditions have generally been bad. So, it is, in practice, an analytical approach that has to serve its purpose for the most part, to figure out those characteristic nuances in static relations, not direct causal implications or anything like that. Especially, "system dynamics" involves the way core principles of general feedback loops are operating; they connect economic activity with things like green externalities, plus policy responses, and these are usually operationalized by time lags, as well as other non-linearities within rather complicated climate-economic systems. It contrasts strongly with long-established econometric methods, or the usual equilibrium notions, because those are fundamentally weak tools since they rely on simulating long-term system behavior that is already implied under different policy reflectors, so they are not as good when you want to estimate climate policies in regions with acute path dependencies or where there are institutional constraints that limit adjustment. Past applications of system dynamics in climate and energy policy studies have shown that it can project emissions trajectories, technology transitions, and policy feedback effects [8]. Still, most of the existing literature has been mostly centered on national or global systems, and it leaves aside regional dynamics such as fossil fuel dependency, inequality, and governance frictions [9, 10]. In the Niger Delta, the record of studies has more or less been limited to the environmental impacts from oil exploitation, gas flaring, and a small number of systems-oriented efforts, linking economic expansion, emissions, and policy responses into a more complete arrangement [11, 12]. This narrowed scope has placed real constraints on policymakers when they try to grasp the long-term outcomes of carbon pricing and the other related interventions for the region. Renewable energy development offers a complementary pathway toward cutting emissions as well as strengthening economic diversification across the Niger Delta. That said, there are costs and policy challenges when trying to smooth out renewable energy development in this region. Investment in the renewable sector, however, holds promise for chipping away at emissions by backing economic stability and creating jobs wherever carbon taxes may have limited energy outreach [13, 14]. The way carbon pricing and renewable energy adoption interact is dynamic, and in practice, it can reinforce feedback loops or interrupt them, which then impacts economic output and environmental outcomes over time.

This paper is an outcome of an investigation conducted into integrated economic growth, carbon pricing, and greenhouse gas emission dynamics in the Niger Delta through a system dynamics model. The basic model hypothesized that industrial activity, emissions from the economic activities, and government intervention interact through the rate of carbon emissions and, therefore, are represented by a simple systems theory model. By simulations of policy counterfactuals, we could see the extent to which carbon pricing could moderate carbon emissions while preserving economic growth. These findings could connect further with climate policy literature on resource-dependent regions and provide a springboard for the possible design of strategies for sustainable development in the Niger Delta.

The Niger Delta is held to be a stressed environment at the sub-Saharan African level, a condition underlaid by decades of hydrocarbons exploitation, which involves widespread gas flaring, deforestation, and industrial development. Though the region is the economic powerhouse of Nigeria and a vital earning point for foreign exchange, the region is severely encumbered by the large share of greenhouse gas emissions and environmental degradation owing to climate variability, continued flooding, loss of ecosystems, and sustained public-health adversities that are a threat to long-term sustainability [15-17]. These environmental oppositions illustrate the wider framework underpinning the new agenda for development, where resource-dependent growth brings economic benefits at the cost of externalizing ecological and social costs, particularly in places with a weak environmental enforcement apparatus.

Carbon pricing has emerged as an internationally acclaimed economic mechanism that sets the stage to reduce carbon emissions by internalizing the social costs of carbon through incentivizing the production of cleaner technologies [18, 19]. Both empirical and theoretical data lend support to the idea that the dynamic operation of carbon pricing would not only spark new technological ventures but would also support renewable energy in places where the corresponding institutional ecosystem supports development [20-22]. However, in economies that need development and are based on fossil fuel use, such as the Niger Delta, there is apprehension about the potential curtailment of economic growth or the increase in production costs through misfitted policies in carbon pricing or otherwise exacerbating previous socio-economic vulnerabilities unless their distributive impacts are carefully managed [23, 24]. Clearly, those concerns point to the need to design policies that are context- based, acknowledging how regional economic structures, and inequality actually work. Even if the weight of carbon pricing in the climate-policy conversation is on the up, the scholarly literature on emissions reduction, and climate policy in Nigeria is still mostly built on relatively fixed empirical ideas, that only capture part of the tangled linkage between economic development, the accumulation of emissions, and the policy adjustments that happen over time. These approaches often disregard feedback effects and the time lag involved, which dominate the long-term behavior of the system. Therefore, the present research is designed to come up with a systems dynamics model-based framework that utilizes the carbon pricing service as a dynamic feedback mechanism for controlling the level of emitted gases and maintaining the economy at its current output. This model allows a thorough quantification of the co-evolution of economic activities, emissions, and government response, thereby providing a quantitative means for evidence-based policy-making that is socially, economically, and scientifically appropriate for the Niger Delta region [25, 26].

2. Model Framework and Structure

The model is defined by four endogenous variables, viz., $Y(t)$, $E(t)$, $P(t)$, and $M(t)$ for economic output, stock of greenhouse gas emissions, carbon price level, and mitigation and clean-technology investment, respectively [27, 28].

The system dynamics model is expressed as:

$$\left.\begin{aligned} \frac{dY}{dt} &= gY - \alpha PY - \chi EY, \\ \frac{dE}{dt} &= \theta Y - \beta ME - \delta E, \\ \frac{dP}{dt} &= \kappa E - \omega P, \\ \frac{dM}{dt} &= \eta P - \mu M. \end{aligned}\right\} \quad (1)$$

2.1. Parameter Description

Table 1 presents the model parameters and their corresponding descriptions.

Table 1. *Model parameters and interpretations.*

Parameter	Description
g	Baseline economic growth rate
α	Sensitivity of output to carbon pricing
χ	Environmental damage coefficient
θ	Emission intensity of output
β	Mitigation effectiveness
δ	Natural emission decay
κ	Carbon price responsiveness
ω	Price adjustment friction
η	Revenue-to-mitigation conversion
μ	Mitigation depreciation rate

2.2. Model Assumptions

The model is developed under the following assumptions, which simplify the underlying dynamics while retaining the essential features of the system.

1) Economic growth follows a baseline exponential path in the absence of policy constraints.
2) Emissions increase proportionally with output.
3) Carbon pricing responds endogenously to emission levels.
4) Mitigation investment is financed through carbon pricing revenues.
5) All parameters are positive and constant over the study horizon.

2.3. Mathematical Properties of the Model

This section establishes the fundamental mathematical properties as regards the model dynamics. For ease of reference, the following are referred to [29-34].

Theorem 2.1 (Existence and Uniqueness). Let the initial conditions satisfy

$$Y(0) \geq 0, \qquad E(0) \geq 0, \qquad P(0) \geq 0, \qquad M(0) \geq 0.$$

Then, the system of differential equations (1) admits a unique solution $(Y(t), E(t), P(t), M(t))$ on any finite time interval $[0, T]$, where $T > 0$.

Proof. Let the state vector be defined as

$$X(t) = \big(Y(t), E(t), P(t), M(t)\big). \quad (2)$$

System (1) can be written in vector form as

$$\frac{dX}{dt} = F(X), \quad (3)$$

where

$$F(X) = \begin{pmatrix} gY - \alpha PY - \chi EY \\ \theta Y - \beta ME - \delta E \\ \kappa E - \omega P \\ \eta P - \mu M \end{pmatrix}. \quad (4)$$

Each component of $F(X)$ is a polynomial function of the state variables Y, E, P, and M. Polynomial functions are continuous and possess continuous partial derivatives with respect to all variables on $\mathbb{R}^4$. Consequently, $F(X)$ is locally Lipschitz continuous on $\mathbb{R}^4$.

By the Picard–Lindelöf theorem, for any given initial condition

$$X(0) = \big(Y(0), E(0), P(0), M(0)\big), \quad (5)$$

there exists a unique local solution to system (1).

To extend this solution to any finite time interval $[0, T]$, observe that the right-hand side of system (1) grows at most linearly with respect to the state variables, since all nonlinear terms are products of bounded coefficients and state variables. Standard continuation results for ordinary differential equations imply that solutions cannot blow up in finite time.

Therefore, the local solution extends uniquely to a global solution on any finite interval $[0, T]$. This completes the proof.

Theorem 2.2 (Positivity and Boundedness of Solutions). Let

$$Y(0) \geq 0, \qquad E(0) \geq 0, \qquad P(0) \geq 0, \qquad M(0) \geq 0.$$

Then every solution $(Y(t), E(t), P(t), M(t))$ of system (1) remains nonnegative and bounded for all $t \geq 0$.

Proof. Positivity. We first show that solutions remain nonnegative for all time. Consider each equation in system (1) separately.

From the output equation,

$$\frac{dY}{dt} = Y(g - \alpha P - \chi E). \quad (6)$$

If $Y(t) = 0$ at some time t, then $\frac{dY}{dt} = 0$. Hence, $Y(t)$ cannot cross from zero into negative values.

Next, consider the emissions equation,

$$\frac{dE}{dt} = \theta Y - \beta M E - \delta E. \quad (7)$$

When $E(t) = 0$, we have $\frac{dE}{dt} = \theta Y \geq 0$. Therefore, $E(t)$ cannot become negative.

Similarly, for the carbon price equation,

$$\frac{dP}{dt} = \kappa E - \omega P, \quad (8)$$

if $P(t) = 0$, then $\frac{dP}{dt} = \kappa E \geq 0$, implying that $P(t)$ remains nonnegative.

Finally, for the mitigation investment equation,

$$\frac{dM}{dt} = \eta P - \mu M, \quad (9)$$

if $M(t) = 0$, then $\frac{dM}{dt} = \eta P \geq 0$. Thus, $M(t)$ cannot cross into negative values.

Since none of the state variables can become negative once they reach zero, the nonnegative orthant

$$\mathbb{R}^4_+ = \{x \in \mathbb{R}^4 : x_i \geq 0,\ i = 1, 2, 3, 4\}$$

is positively invariant under system (1). Hence, all solutions remain nonnegative for all $t \geq 0$.

Boundedness. We now show that the solutions are bounded for all $t \geq 0$. From the output equation,

$$\frac{dY}{dt} \leq gY, \quad (10)$$

since the terms αPY and χEY are nonnegative. By Grönwall's inequality,

$$Y(t) \leq Y(0)e^{gt}, \quad (11)$$

for all $t \geq 0$.

Using this bound in the emissions equation, we obtain

$$\frac{dE}{dt} \leq \theta Y(0)e^{gt} - \delta E. \quad (12)$$

This is a linear differential inequality whose solution implies that $E(t)$ remains bounded for all $t \geq 0$.

Next, consider the carbon price equation,

$$\frac{dP}{dt} \leq \kappa E - \omega P. \quad (13)$$

Since $E(t)$ is bounded, standard comparison arguments show that $P(t)$ is also bounded.

Finally, from the mitigation equation,

$$\frac{dM}{dt} \leq \eta P - \mu M, \quad (14)$$

and the boundedness of $P(t)$, it follows that $M(t)$ is bounded for all $t \geq 0$.

Combining these results, all state variables $Y(t)$, $E(t)$, $P(t)$, and $M(t)$ remain bounded for all $t \geq 0$. This completes the proof.

Theorem 2.3 (Local Stability of the Low-Emission Equilibrium). Suppose that the equilibrium state (Y^*, E^*, P^*, M^*) exists and satisfies the condition

$$\kappa\eta > \theta\mu.$$

Then the equilibrium is locally asymptotically stable.

Proof. Local stability is determined by the eigenvalues of the Jacobian matrix of system (1), evaluated at the equilibrium point.

Let the vector field be written as

$$X = (Y, E, P, M). \quad (15)$$

The Jacobian matrix $J(X) = DF(X)$ is given by

$$J = \begin{pmatrix} g - \alpha P - \chi E & -\chi Y & -\alpha Y & 0 \\ \theta & -\beta M - \delta & 0 & -\beta E \\ 0 & \kappa & -\omega & 0 \\ 0 & 0 & \eta & -\mu \end{pmatrix}. \quad (16)$$

Evaluating this Jacobian at the equilibrium (Y^*, E^*, P^*, M^*), we obtain

$$J^* = \begin{pmatrix} g - \alpha P^* - \chi E^* & -\chi Y^* & -\alpha Y^* & 0 \\ \theta & -\beta M^* - \delta & 0 & -\beta E^* \\ 0 & \kappa & -\omega & 0 \\ 0 & 0 & \eta & -\mu \end{pmatrix}. \quad (17)$$

At the low-emission equilibrium, the economic and emissions subsystems are regulated by the policy feedback loop involving carbon pricing and mitigation investment. The Jacobian matrix J^* has a block lower-triangular structure, which allows its eigenvalues to be analyzed through its diagonal blocks.

The subsystem governing the interaction between carbon pricing and mitigation investment is described by the matrix

$$A = \begin{pmatrix} -\omega & 0 \\ \eta & -\mu \end{pmatrix}, \quad (18)$$

whose eigenvalues are $-\omega$ and $-\mu$, both strictly negative.

The coupling between emissions and policy dynamics introduces an effective feedback gain proportional to $\kappa\eta$, while emissions generation depends on the term $\theta\mu$. The condition $\kappa\eta > \theta\mu$ ensures that the stabilizing feedback from adaptive carbon pricing and mitigation investment dominates the emissions growth induced by economic activity.

Under this condition, the real parts of all eigenvalues of J^* are strictly negative. Consequently, perturbations away from the equilibrium decay exponentially over time.

By the Hartman–Grobman theorem, the nonlinear system (1) is locally asymptotically stable around the equilibrium (Y^*, E^*, P^*, M^*). This completes the proof.

3. Differential Transform Method

The Differential Transform Method (DTM) is used to obtain semi-analytical approximations of differential models [14, 26]. In what follows, the concept of the DTM will be adopted for the model approximate solutions. Hence, for a function $X(t)$,

$$X(k) = \frac{1}{k!}\left[\frac{d^k X(t)}{dt^k}\right]_{t=0}, \tag{19}$$

with inverse transform

$$X(t) = \sum_{k=0}^{\infty} X(k)t^k, \tag{20}$$

the recursive algebraic relations for $Y(k)$, $E(k)$, $P(k)$, and $M(k)$ are easily obtained. This will be embedded in the simulation processes.

4. Numerical Experiments and Illustrative Examples

To show the usefulness and interpretative strength of the proposed system dynamics model, we carry out a set of numerical experiments with varying parameter arrangements, sometimes a bit tricky. The experiments show the economic growth trajectories, carbon pricing mechanisms, and greenhouse gas emissions as having a dynamic interaction through time, and that the policy parameters have an influence on both the transient responses and the long-term system behavior.

4.1. Parameter Values

Table 2 summarizes the baseline parameter values used in the numerical simulations.

Table 2. *Baseline parameter values used in simulations.*

Parameter	Value
g	0.05
α	0.02
χ	0.01
θ	0.30
β	0.04
δ	0.02
κ	0.25
ω	0.10
η	0.20
μ	0.08

The corresponding initial conditions are as follows:

$$Y(0) = 100, \qquad E(0) = 40, \qquad P(0) = 5, \qquad M(0) = 10.$$

4.2. Sensitivity Analysis of the Model

To assess the robustness of the model results, a one-at-a-time sensitivity analysis was conducted using the baseline parameter values in Table 2. The parameters g, α, θ, β, κ, and η were varied by $\pm 10\%$ and $\pm 20\%$, while the remaining parameters were held constant.

Particular attention was given to the carbon-price responsiveness parameter κ, which determines the strength of the policy response to changes in greenhouse gas emissions. The effects of parameter variations were assessed primarily through the trajectories of economic output $Y(t)$ and greenhouse gas emissions $E(t)$, with the corresponding responses of carbon price $P(t)$ and mitigation investment $M(t)$ also considered.

The sensitivity results provide an assessment of the robustness of the model outcomes and identify the parameters that have the greatest influence on the balance between economic growth and emissions reduction. The results are presented graphically and complement the policy scenarios discussed in Section 4.3.

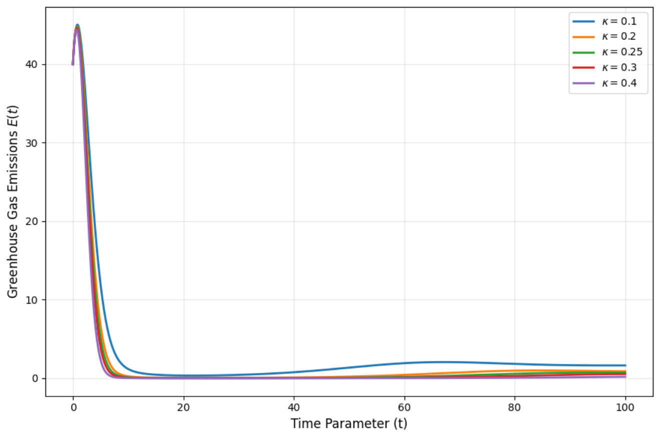

Figure 1. *Sensitivity of GHG Emissions to Carbon-Price Responsiveness κ.*

As regards the sensitivity analysis of the carbon-price responsiveness, Figure 1 illustrates the sensitivity of greenhouse gas emissions $E(t)$ to variations in the carbon-price responsiveness parameter κ. The results show that changes in κ produce distinct emissions trajectories, indicating that the strength of the carbon-pricing response plays an important role in the evolution of greenhouse gas emissions. Higher values of κ represent a stronger response of carbon pricing to rising emissions and consequently enhance the policy feedback mechanism, while lower values correspond to weaker policy responses. The sensitivity of the emissions trajectories to κ demonstrates the importance of an appropriately responsive carbon-pricing mechanism in achieving sustained emissions reduction.

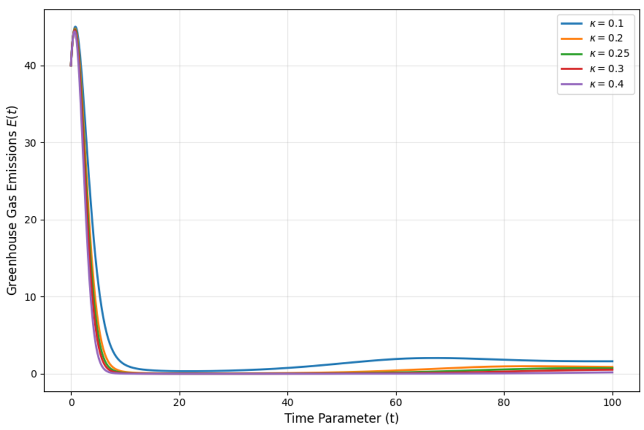

Figure 2. Sensitivity of GHG Emissions to Emission Intensity Parameter θ.

For the sensitivity to emission intensity, Figure 2 shows the sensitivity of greenhouse gas emissions $E(t)$ to variations in the emission intensity parameter θ. The results indicate that changes in θ substantially influence the emissions trajectory, reflecting the direct contribution of economic output to greenhouse gas generation. Higher values of θ represent greater emission intensity and consequently lead to stronger emissions pressure, whereas lower values indicate a less emission-intensive production structure. The result highlights the importance of reducing the carbon intensity of economic activities alongside the implementation of carbon-pricing policies.

4.3. Scenario Analysis

Case 1: No Carbon Pricing ($\kappa = 0$)

In this baseline scenario, carbon pricing is completely deactivated by setting the policy responsiveness parameter to zero ($\kappa = 0$). Consequently, the carbon price variable remains constant at $P(t) = 0$ throughout the simulation period. Economic growth therefore evolves without regulatory constraints, while greenhouse gas emissions respond solely to output expansion.

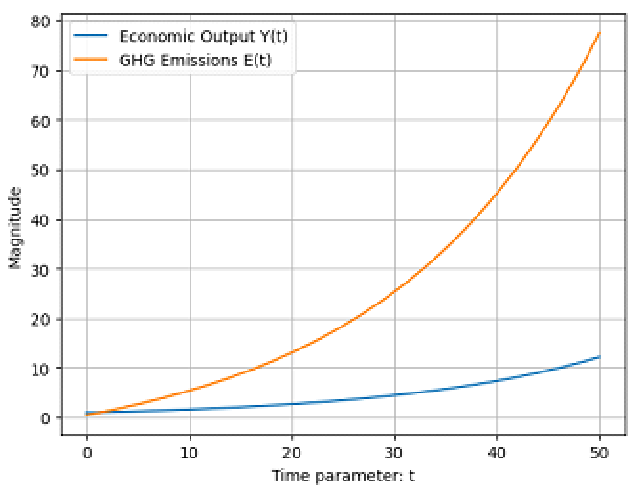

Figure 3. Economic output and emission trajectories without carbon pricing.

The Figure 3 illustrates the temporal evolution of economic output $Y(t)$ and greenhouse gas emissions $E(t)$ when no carbon pricing mechanism is in place. Economic output exhibits sustained exponential growth, reflecting unrestricted industrial and energy-intensive activities. Correspondingly, emissions increase monotonically over time, closely tracking output growth.

4.4. Findings and Interpretation for Case 1– No Carbon Pricing

The results suggest that the economic development of the Niger Delta region is indeed a scenario where carbon offsets and carbon credit markets are not operating. It is not surprising that environmental policies that impose production cost recovery measures are still at the planning stage. The region is evidently going through a "business-as-usual" stage where the environment is tolerant of being mistreated for a short period in exchange for quick economic gains.

The continuous upward trend of emissions implies that the carbon in the atmosphere is being collected at a fast rate, which in turn, increases the susceptibility of the climate to risks such as floods, coastal erosion, and habitat loss in the Niger Delta. For the lawmakers, this scenario is a source of concern that the reduction of regulatory barriers to economic growth will result in the same situation as if nothing had been done, but asking for higher emissions allowances. This thus emphasizes the need for more regulatory policies, such as carbon pricing, and calls for a further assessment of their effectiveness in the future.

Case 2: Weak Carbon Pricing ($\kappa > 0$, small)

Under such conditions, carbon pricing is imposed with a low policy reaction, which is indicated by a small, albeit positive, value of the policy adjustment parameter ($\kappa > 0$). Accordingly, the carbon price $P(t)$ goes up slowly throughout the period but stays at a relatively low level, thus only having a slight impact on the regulation of economic activities and emissions. The economic growth is majorly unaffected, while the emissions of greenhouse gases are lessened to some extent due to the weak pricing signal. Weak pricing signal leads to partial emissions reduction.

The temporal evolution of greenhouse gas emissions $E(t)$ under very low carbon pricing is illustrated in Figure 4. Emissions in the pricing case slightly drop and thus grow at a lower rate than in the case where there is no pricing, showing the modest but still existing dampening effect of the carbon price. Nevertheless, the emissions trend is still rising, which means that the pricing is not strong enough to eliminate or even stop the growth of emissions.

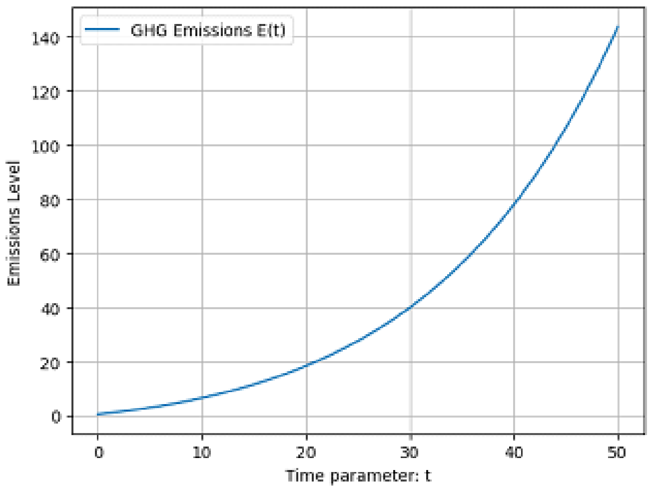

Figure 4. Emission dynamics under weak carbon pricing.

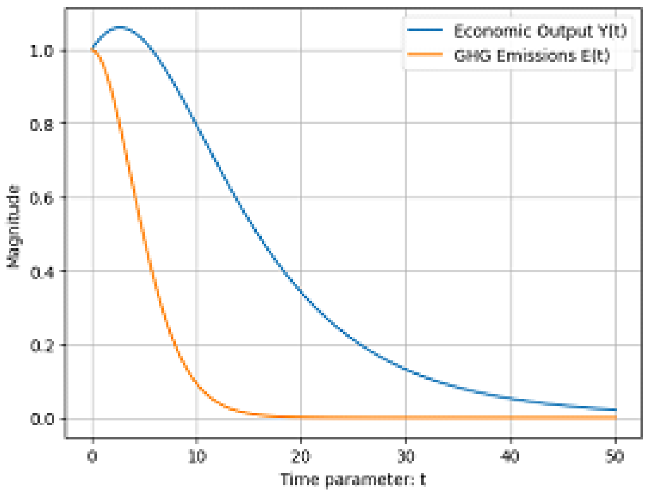

Figure 5. Output–Emission Decoupling under Adaptive Carbon Pricing.

4.5. Findings and Interpretation for Case 2 (Weak Carbon Pricing)

The results indicate that the implementation of a low carbon price does not cause any large consumption of carbon in the Niger Delta, as it only has a small impact. The low carbon price brings about a gradual increase in emissions, but it is not strong enough to eliminate the emissions resulting from the ongoing economic growth. Hence, the total emissions rise, but at a slower pace compared to the business-as-usual scenario.

The case study has significant implications for policy, saying that marginal, or weak carbon pricing schemes may lower the rate of carbon emissions, but they are unable to deliver results in the area of long term mitigation. The findings, from the study suggest that more stringent carbon pricing policies, and gradually escalated ones, need to be introduced so that the objective of reducing emissions can be met without risking economic development.

Case 3: Adaptive Carbon Pricing

In this situation, carbon pricing is established as a flexible policy tool that reacts intensely to changes in the greenhouse gas emissions level. The policy ability to respond, shown by the parameter κ, is set at a high value, so that the carbon price $P(t)$ can jump quickly when emissions go up. As emissions increase, carbon prices climb as well, and this then feeds back into the economic and emissions subsystems, to discourage production that is carbon-intensive, and to stimulate cleaner technologies.

The joint dynamics of economic output $Y(t)$ and greenhouse gas emissions $E(t)$ under adaptive carbon pricing are presented in Figure 5. Despite the continuous growth of economic output, the increasing carbon price serves to moderate its growth rate. On the other hand, emissions first go up but then level off and fall as the mechanism of adaptive pricing gets stronger. This divergence between output and emissions demonstrates a clear decoupling effect brought on by the policy.

4.6. Findings and Interpretation for Case 3–Adaptive Carbon Pricing

The findings from this research suggest that an adaptive carbon pricing system is notably more efficient than relying on a static , or even weak price strategy. The carbon price, which is dynamically adjusted based on the growth of emissions, is in fact gradually integrating environmental costs into the economic system, so that emissions can be reduced over a long period without needing a full shutdown of the economy. The storyline where emissions are reduced steadily and later stabilize shows that the rigorous but necessary mitigation has been completed, while everything continues, and yes the economy is still flourishing.

From the point of view of the policy, the situation underlines the importance of a carbon pricing design to be dynamic and flexible. The government can apply the adaptive pricing systems to arrive at a point where economic development and environmental conservation can coexist, which is the case in the region of the Niger Delta, where emissions-heavy growth has always been the root of environmental degradation.

Case 4: Delayed Policy Response

In this case, the implementation of carbon pricing takes place only when there is already a considerable amount of greenhouse gases in the atmosphere. Such a scenario is envisioned by permitting the emissions to increase without restrictions for a certain initial period, followed by the imposition of carbon pricing. Consequently, the carbon price $P(t)$ reacts too late and thus, the high emissions corresponding to the carbon-intensive growth that take place before the pricing get locked in.

In the delayed policy intervention scenario, Figure 6 demonstrates the temporal dynamics of economic output $Y(t)$ and CO_2 emissions $E(t)$. In the absence of regulations, the early stage sees a rapid increase in emissions together with economic output. The introduction of carbon pricing, however, results in a slowdown of the growth in emissions; nevertheless, the total emissions continue to be extremely high for a long time.

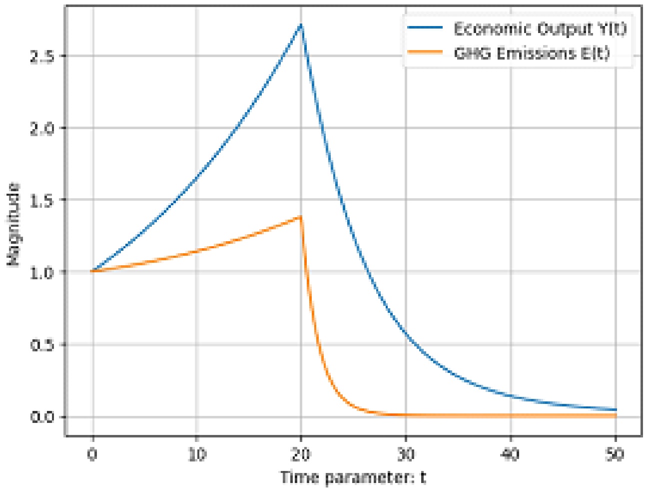

Figure 6. *Lock-in Effects Caused by Delayed Carbon Pricing.*

The results showed that the introduction of carbon pricing after a certain period renders emissions reduction much less effective. The pricing responds to emissions from the very beginning of law enforcement, but the delay in the intervention allows already high-carbon production facilities to be built. The lock-in effect, in turn, causes the environmental damage to continue even after the measures to reduce emissions have been taken.

From a policy perspective, this case suggests that the non-application of CO_2 pricing may lead to an irreversibly long ecological disaster in the future. It underlines the importance of timely and strong climate policy actions in the Niger Delta, where the regulation delays can cause emissions to build up and thus hinder the achievement of the sustainability goals set for the long term.

5. Concluding Remarks

A systems dynamics methodology was utilized to investigate the interrelation of economic growth, carbon pricing, and greenhouse gas emissions in the Niger Delta, which is a very dynamic environment. The analysis under different policy scenarios unveils the role of carbon pricing as a key factor: its existence, its intensity, and the timing of its influence on the paths of long-term emissions and the corresponding economic gains.

The scenario with no carbon pricing clearly shows a very close and direct relationship between emissions and economic activity. In this scenario, production increases without being restricted by any regulation, and emissions grow continuously as a result. Although short-term economic advantages are present, the absence of policy feedback leads to uncontrolled environmental degradation and thus, the business-as-usual path is reinforced, which is contrary to the long-term climate and sustainability objectives in the Niger Delta.

The installation of a carbon pricing policy, where the reaction of the policy is nothing more than weak, does not even provide a modest increment in the situation. The carbon price may slowly be ramped up, but at the same time, total emissions are still accumulating. These are the conditions under which very low or simply token carbon pricing may reflect an environmental concern, but are too feeble to bring about a change in the attitude towards production or the intensity of emissions. Therefore, weak pricing extends the period of environmental pressure instead of stopping it.

On the contrary, adaptive carbon pricing is touted as a highly effective policy measure. When carbon prices are responsive and react strongly to the volumes of emissions, one can see that the economic activity and the emissions have grown apart. The level of emissions from the economy is still considerable, but due to being made less and less appealing over time and the extension of the mitigation efforts, the emissions reach the point where they are stabilized and even reduced. The example shows that if the right and very responsive policy mechanism for reducing emissions is in place, one does not have to forfeit economic growth.

The example of the lagged policy response stresses the importance of timing even more. When carbon pricing is implemented after emissions have already been quite high, it does not play a very effective role in mitigating the situation. When early expansion is left unchecked, the whole system gets pushed toward a higher emission path, and then later actions can be far less useful, like trying to pull a tide back once it has already moved. In other words, the harm is already in motion, and intervention after the fact struggles to undo the environmental damage that has already accumulated. Here, the long-run costs of delaying climate policy become especially visible in places where fossil fuel activities dominate, because the local economic structure tends to revolve around extraction and related work. So, the study, in summary, points to three main things. First, if there is no carbon regulation, and economic growth keeps going, emissions climb steadily. Second, weak, missing, or postponed carbon pricing does not deliver much for meeting mitigation goals, even when policymakers assume it will. Third, putting in place early and flexible carbon pricing is presented as the main lever to reconcile economic progress with the preservation of the natural environment. In the Niger Delta, where material wealth and high sensitivity to ecological harm are present at the same time, preemptive and adjustive carbon pricing should be treated as an unavoidable requirement, not a choice. The system dynamics framework envisioned here serves as a numerical backbone for evaluating how climate and economic policies interact in resource- dependent regions. The model could then get a bit further refined, by doing empirical calibration with data from the particular area, splitting the different sectors, and also bringing in random climate shocks. With these advancements, the setup would not only become more useful for policy strategy, and long- term sustainability planning, but it would also turn out even more resilient.

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Abbreviations

DTM	Differential Transform Method
GHG	Greenhouse Gas
MA	Model Assumption
ODE	Ordinary Differential Equation
NERIST	North Eastern Regional Institute of Science and Technology
ICCM	International Conference on Computers, Management and Mathematical Sciences
TETFund	Tertiary Education Trust Fund
IBR	Institution-Based Research

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Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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