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Research article

Mitigating Greenhouse Gas Emissions from Rice Production in the Philippines: A System Dynamics Approach

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Abstract: Greenhouse gases (GHG) emissions from agricultural production, most especially from methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddies and from excessive use of fertilizers, contribute significantly to global warming. This paper presents a system dynamics (SD) model to forecast agricultural GHG emissions and rice production in the Philippines over a fourteen year time horizon (2026 to 2040) under four different scenarios. These scenarios are: a) the conventional method of irrigation used by farmers today, b) Alternate Wetting and Drying (AWD) of puddles created during flooded rice cultivation, applied in combination with biochar amendments (AWD & biochar), c) Urea Deep Placement (UDP) which is a precise placement of nitrogen containing fertilizers, and d) mechanization of animal powered tillage (mechanization). The model was validated against independent benchmarks for agricultural emissions with Mean Absolute Percentage Errors (MAPE) ranging from 0.96% to 1.52%. The results obtained from the different scenarios showed that Scenario 2 (AWD & biochar) resulted in the largest average emissions reduction of 25% (range: 23%–27%) and highest average rice yields of 6.81% (range: 5%–8%) over the entire 14-year period compared to the baseline. Scenario 3 (UDP) yielded average emissions reduction of 4.5% (range: 4%–5%) and average increase in rice yields of 5.42% (range: 4%–6%). The fourth scenario or mechanization of animal powered tillage yielded minimal average emissions reduction of 0.2% (range: 0.2%–0.3%) and average increase in rice yields of 0.04% (range: 0%–0.1%). These percent changes in emissions and yield reported in the paper are averages over the entire 14-year period and are computed on an annual basis by comparing each year in the four scenarios with corresponding years in the baseline scenario. Results indicate that two approaches namely AWD with biochar and UDP whether singly or in combination are most feasible near-term options to develop climate smart agriculture or climate smart rice production in the country and are within the country's Nationally Determined Contributions (NDCs) under the Paris Agreement.

Keywords: GHG emissions; system dynamics modeling; alternate wetting and drying

1. Introduction

Rice production is one of the world's most critical and growing industries, supplying more than half of the world's population with up to 20% of their daily calorie intake [1]. But it is also a major emitter of carbon dioxide equivalent emissions [2], particularly of two of the most powerful climate change gases: methane (CH_4)[3,4] and nitrous oxide (N_2O)[5]. Methane is emitted during

rice production, primarily in flooded paddies where the organic material undergoes anaerobic decomposition. With global demand for rice set to increase in the years to come, it is essential to find more sustainable ways of producing this fundamental crop [6].

Agriculture is a significant contributor to the Philippine economy, and rice is a crop that plays a vital role in ensuring the country's food security. At the same time, agricultural activities, especially rice production, are also responsible for the increase in Greenhouse Gas (GHG) emissions from the country. Most of these emissions are attributed to the permanently flooded rice paddies, which have been found to be significant sources of methane. Cultural, economic, and environmental factors interact in complex ways in agricultural production ecosystems. As a precursor to the search for solutions to this complex problem, it is important to know the contribution of rice production to the country's emissions.

A limited number of studies have applied system dynamics (SD) modeling to characterize GHG emissions from rice production systems in the Philippines [7]. While there are many studies on agricultural emissions, very few are comprehensive, covering the whole system and its long-run consequences. System dynamics modeling is well-suited for simulating complex systems such as rice production and consumption. It offers a systems perspective to address GHG emissions from rice production. A more robust SD model is needed to simulate and understand the country's rice production system and to formulate more informed policies and strategic interventions to address GHG emissions from rice production.

The novel contribution of this study is the development of a national-scale Philippine SD model that integrates irrigated and non-irrigated rice area dynamics, yield responses, and area-weighted GHG emission factors within a single simulation framework. This helps in formulating pragmatic policies to increase agricultural productivity while safeguarding the environment. For attaining sustainable agriculture, three objectives were formulated for the present study. 1) Develop and validate the SD model for assessing GWP of rice crop in Philippines. 2) Analyzing the impact of three mitigation options i.e. AWD with biochar application, UDP and mechanization on GWP and rice yield from 2026 to 2040. 3) Formulate policy based on research findings.

1.1 Greenhouse Gas Emissions and Modeling Techniques

Estimation of the Global Warming Potential (GWP) emissions of Greenhouse Gases (GHGs) from rice crops using different modeling methodologies has been widely studied. These emissions (including CO2, CH_4 and N_2O) are considered major contributors to global warming. Emissions of GHGs come from various sources, including energy, transportation, industry, and agriculture. In the agricultural sector, a number of modeling methodologies have been applied, including statistical models, process-based models, life cycle assessment (LCA) [8], integrated assessment models (IAMs) [9], and system dynamics (SD) modeling [7, 10, 11]. To understand and predict trends and correlations in historical data, time series analysis is a common approach. However, it is not suited for making educated guesses about underlying long-term processes for future scenarios [12]. In contrast, process-based models can be used to simulate certain processes in more detail, and some greenhouse gases are considered state of the art [13]. However, to drive such models with relevant data, much remains to be done. Time-consuming Life Cycle Assessment is well suited to identify emission hotspots but impractical for larger dynamic systems. Integrated Assessment Models (IAMs) offer the only way to model economies, environments, and societies simultaneously. However, IAMs are very complex models, sensitive to many uncertainties, and are often considered too simple for real-world systems.

In contrast to static descriptor models, SD modeling has drawn significant attention as a more general tool for analyzing global climate change impacts and costs across sectors, including agriculture, energy, and urban systems. SD models allow the explicit representation of feedbacks, delays and nonlinear relationships which are relevant for long-term mitigation projections. Additional features of SD models include their ability to handle multiple data sources and disciplines to map relevant determinants of GHG emissions. As the world launches a grand initiative to curb climate change, the need for effective yet flexible modeling tools, such as SD modeling, is likely to increase.

2. Materials and Methods

2.1 System Dynamics Approach

A System Dynamics approach has been used to develop a simulation model to predict and analyze GHG emissions from rice cultivation. The SD approach consists of five steps for building a model: problem articulation, dynamic hypothesis formation, model formulation, model validation, and policy analysis. The problem articulation consists of specifying the research question, the system boundary and the objectives of the study. The dynamic hypothesis formation constructs a conceptual image of the real system under study and aims to understand its underlying mechanisms and dynamics. The model formulation transforms the conceptual image into a quantitative simulation model; i.e., the model's equations are written down for the state variables and their related parameters. The model validation tests the model's ability to simulate past scenarios, analyses the model's sensitivity to input variables and parameters, and studies the model's behavior under variations in initial conditions and assumptions. The policy analysis utilises the validated model for prediction and for analysing impacts of different agricultural practices and management options on rice production and GHG emissions. The model was implemented in Stella Architect 4.3.1 using a one-year time step and the Euler integration method.

2.2 Model Scope and Boundaries

This SD model for Philippine national rice production system. The model runs over a 14 year time horizon, from 2026 until 2040. The historical calibration period for the model is from 2000 until 2020. Two production systems for rice are modeled: irrigated rice and non-irrigated or rainfed rice. The following state variables are tracked by the model: irrigated rice area (ha), non-irrigated rice area (ha), irrigated rice yield (t/ha), non-irrigated rice yield (t/ha), total local rice production (t), and total GHG emissions (kg CO_2eq.ha/yr).

The SD model includes on-farm emissions from growing rice and fertilizer use on farms such as methane (CH_4) emissions from flooded rice paddies and emissions of nitrous oxide (N_2O) from inorganic fertilizer use. In addition, enteric and manure methane (CH_4) emissions are included from carabao (water buffalo) used for tillage in Scenario 4. Upstream emissions of greenhouse gases from production of fertilizer, machinery, energy for irrigation, postharvest losses from rice and transport of rice are not included in the model as these are outside the model boundary and represent a limitation of the current model. Table 1 summarizes the principal model variables.

2.3 Data Collection and Model Parameterization

Several studies were reviewed for model parameters, including historical production of rice in different ecosystems (i.e. irrigated rice and rainfed lowland rice) and harvested area of rice in different ecosystems by Philippine Statistics Authority (PSA) for the years 2000–2020 [17]. The emission factors of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) for cultivated rice (irrigated and rainfed lowland) were obtained from life-cycle assessment studies on rice systems in the Philippines by Bautista et al. [8]. In addition, the emissions from enteric fermentation and manure from carabao were also obtained from Bautista et al. [8].

For the above scenarios a number of parameters were defined, primarily based on data from studies which have investigated the effects of different rice interventions and in particular their impact on greenhouse gas emissions. The use of AWD systems for irrigated rice in Southeast Asia were modeled based on average CH_4 emission reduction and increase in rice yield as reported in a limited number of quantitative studies. Biochar and UDP scenarios were modeled based on the effects of biochar amendment as reported in a number of studies, and the effects of UDP as reported in one study. The effects of AWD and biochar amendment were modeled as a single 'blended' scenario (Scenario 2) since there is partial overlap of the sources of emissions that can be reduced by these two interventions, rather than as having additive effects.

The emission factors used in this study are from Bautista et al. [8] which were published in 2005 or when Philippine rice systems were mostly characterized by old technologies, thus the emission factors are generally high. Although the emission factors are the most comprehensive and nationally specific for rice systems in the country, sensitivity analysis of results to ±20% variation in emission factors are presented in Section 2.5.

Table 1. Summary of Principal Model Variables

Variable	Definition	Unit	Source / Assumption	Initial Value	Notes
Irrigated Rice Area	Total harvested area under irrigated rice	ha	PSA [17]	3,340,000	Initial value from 2022 PSA data
Non-Irrigated Rice Area	Total harvested area under rainfed rice	ha	PSA [17]	1,460,000	Initial value from 2022 PSA data
Irrigated Rice Yield	Average yield per harvested hectare (irrigated)	mt/ha	PSA [17]; scenario adjustments from [18,19,20]	4.47	Scenario-specific yield multipliers applied
Non-Irrigated Rice Yield	Average yield per harvested hectare (rainfed)	mt/ha	PSA [17]	3.29	Not affected by AWD (rainfed cannot use AWD)
GHG Emission Factor – Irrigated	Average on-farm emission per hectare of irrigated rice	Kg CO_2eq./ha/yr	Bautista et al. [8]	3,920	Modified by scenario policy switches
GHG Emission Factor – Non-Irrigated	Average on-farm emission per hectare of non-irrigated rice	Kg CO_2eq./ha/yr	Bautista et al. [8]	1,380	Unchanged in Scenarios 2–3; unaffected by AWD
Total GHG Emissions	Sum of irrigated and non-irrigated rice emissions	Kg CO_2eq./ha/yr	Equation (1)	GHG Emission of Irrigated rice + GHG Emission of Non-Irrigated Rice	Annual output variable
Available Arable Land	Fixed total land available for rice conversion	ha	PSA [17]	5,460,000	Upper constraint for both land-area feedback loops

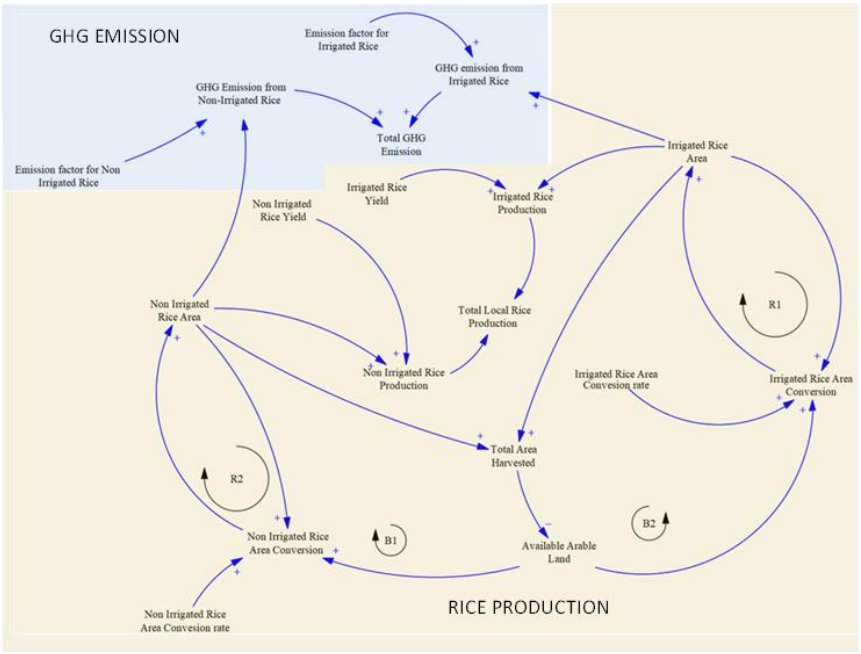


Figure 1. Model Structure Framework of the Study in Causal Loop Diagram

2.4 Model Structure and Feedback Loops

2.4.1 Reinforcing Loops

The two reinforcing loops in the causal loop diagram show how increases in both irrigated and non-irrigated rice areas can create self-reinforcing (positive feedback) dynamics. The Irrigated Rice Area Conversion (R1) shows that a more irrigated rice area encourages and enables more land conversion to irrigated rice, which in turn accelerates the rate of conversion. The expanding irrigated rice area, in turn, encourages and enables further expansion, leading to increasing growth in irrigated rice area. A similar reinforcing loop, the Non-Irrigated Rice Area Conversion (R2), depicts the dynamics of converting non-irrigated (rainfed) rice. Areas cultivating non-irrigated rice have increased, mainly due to shifts to non-irrigated rice cultivation, possibly driven by easier cultivation under rainfed conditions or higher yields to meet increasing food demand. This process of converting to non-irrigated rice cultivation has further increased the total areas under non-irrigated rice cultivation and has continued to expand.

2.4.2 Balancing Loop

The balancing loops in the Causal Loop Diagram act to limit the growth promoted by the reinforcing loops as resources become scarce. The irrigation of additional land to increase the area of rice production in due course reduces the Available Arable Land (Balancing Loop B1). Available Arable Land is a fixed quantity of land. In due course, the amount of land available reduces, thereby reducing the rate at which more land can be converted to irrigated rice. The irrigated rice area in due course therefore reduces to a level that stabilises the system, limiting growth as the land capacity diminishes to a natural limiting value. Similarly, Balancing Loop B2 limits the expansion of Non-Irrigated Rice Area. In this relation, increase of Non-Irrigated Rice Area (NIRA) leads to a decrease of Available Arable Land (AAL). Hence, the rate of conversion of unirrigated cropped land into NIRA is reduced. With further decrease of AAL, the growth of non-irrigated rice is finally stopped. The two balancing loops B1 and B2 act in opposition to the reinforcing loops R1 and R2, imposing limits to growth based on the finite availability of land. They keep the system sustainable by preventing rice farming from growing indefinitely.

2.5 Model Validation

The SD model is validated by checking all the equations in the model for dimensional consistency. The model is also tested for extreme conditions, i.e. emission factors and adoption rates are set to zero and to their maximum possible values, and the resulting outputs are checked for reasonableness.

The MAPE of the GHG emission outputs calculated for the calibration period are shown in Table 2 for total GHG emissions, irrigated rice and non-irrigated rice emissions and compared to the reference values obtained from the same literature used for the parameterization of the model (Bautista et al. [8]). The percentage errors calculated for the total GHG emissions from rice production in the Philippines for the calibration period were 1.21%, 1.52% and 0.96% for total, irrigated and non-irrigated rice emissions, respectively. The errors calculated were below the typical error threshold of 5% used for SD model validation. Note, however, that the reference dataset used for the comparison in the calibration period was based on the same emission factor literature that was used for the model's parameterization (Bautista et al. [8]). Full independent historical emission time-series data for the Philippine rice systems at national scale are not available yet for the validation of the model's outputs. This is treated as one of the limitations of this study.

2.6 Sensitivity and Uncertainty Analysis

One way to assess the uncertainty in a projected trend is to test the sensitivity of that trend to changes in one parameter at a time. We here report the results of a one-at-a-time (OAT) sensitivity analysis for the projected trends for GHG emissions as well as for crop yields, i.e. for all end points, in which all key parameters (one at a time) were varied by 20% around their base case values. In the case of the biochar parameters, the biochar yield improvement factor (YBIO) was varied by 20% as well. The growth rate of irrigated rice (pRI) was varied by 15% and available arable land (pSA) ceiling was varied by 10% around its base case value in both directions. The results of this sensitivity test are plotted as uncertainty bounds around the respective trends in the Results section.

The results of the one-at-a-time sensitivity analysis, conducted to test the sensitivity of results to uncertainties in the values of the parameters, showed that all changes were within moderate to low bounds. In terms of GHG emissions reduction, all tested values for the Scenario 2 results yielded between 23% and 27% reduction of greenhouse gas emissions from agriculture, below those of a no mitigation scenario. The results for Scenario 3 yielded a reduction of GHG emissions from agriculture between 4.5% and the upper limit of 5%. The results for Scenario 4 yielded results all below 0.3% change and thus the sensitivity analysis produced the same results for all test cases. Therefore, the results for Scenario 2 were presented in the results in Section Results for Scenario 2 with the results shown as a range of results with associated uncertainty bounds. Ideally, a stochastic sensitivity analysis would be conducted to take into account correlations between the parameters, which were treated as independent variables in the above one-at-a-time sensitivity analysis.

Table 2. Model Validation Results – MAPE

Validation Variable	MAPE (%)	Years Compared
Total GHG Emissions from Rice Production (Simulated vs. Reference)	1.21	2000–2019 (PSA production data; Bautista et al. emission factors)
GHG Emissions from Irrigated Rice Production (Simulated vs. Reference)	1.52	2000–2019
GHG Emissions from Non-Irrigated Rice Production (Simulated vs. Reference)	0.96	2000–2019

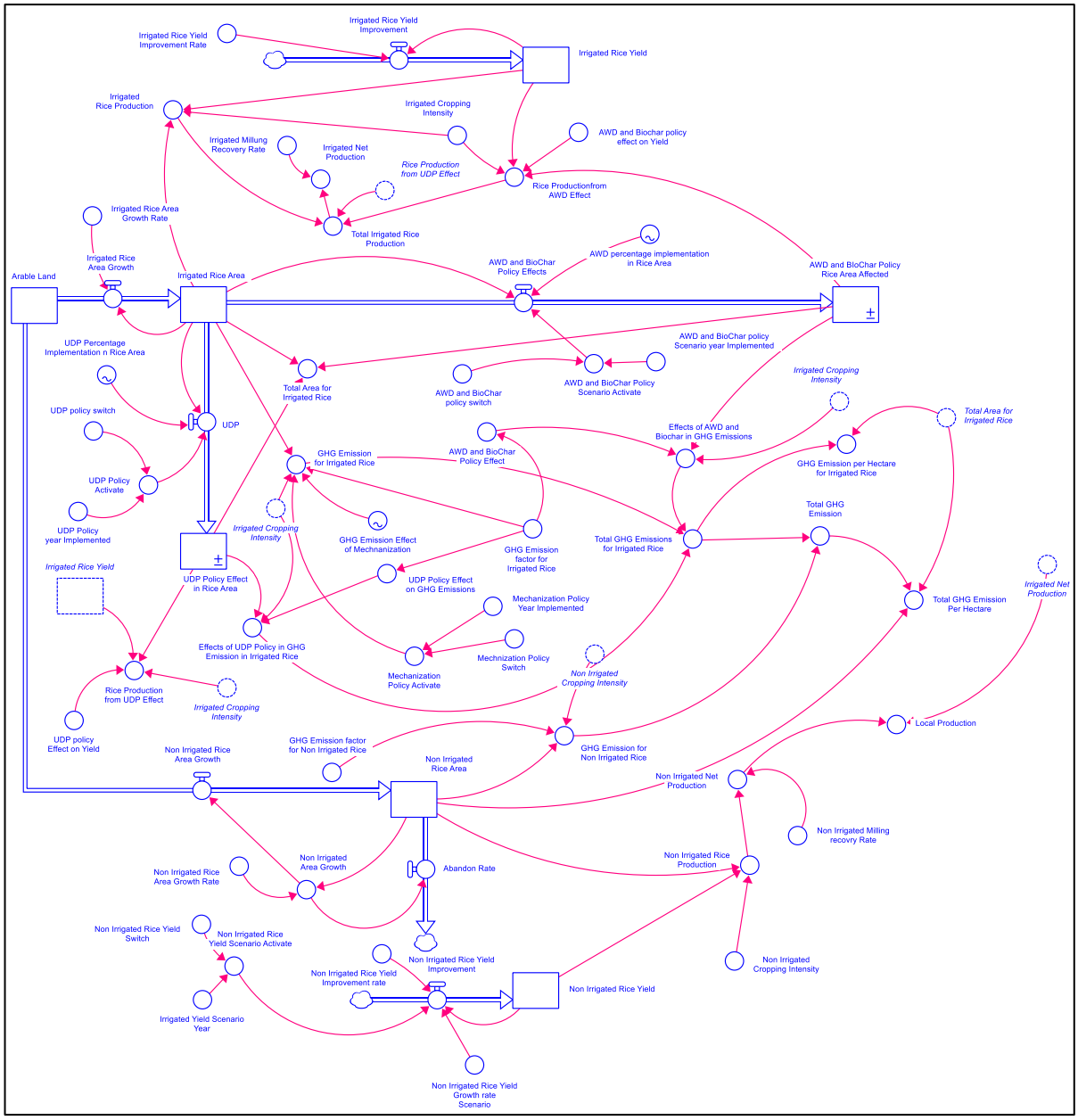


Figure 2. Stock and Flow Diagram of the GHG Emission of the Rice Production in the Philippines

3. Results and Discussion

3.1 Scenario Development and Assumptions

Table 3 summarizes the four scenarios, their target interventions, parameter adjustments, emission mechanisms, and expected outcomes.

Table 3. Scenario Summary: Assumptions, Parameter Changes, and Mechanisms

Scenario	Intervention	Parameter Changed	Emission Mechanism Targeted	Expected Outcome (Modeled)
S1 – Baseline	Conventional continuous flooding; no mitigation	None (reference)	CH_4 from flooded paddies; N_2O from broadcast urea	Reference trajectory for emissions and yield
S2 – AWD + Biochar	Alternate Wetting and Drying combined with biochar soil amendment applied to irrigated rice areas	Emission factor (irrigated): −35% AWD, −20% biochar (blended, non-additive); yield (irrigated): +28% biochar	CH_4 suppression via soil aeration (AWD); additional methanogenesis suppression and C sequestration (biochar)	Average −25% GHG emissions; +6.81% yield over 2026–2040 vs. S1
S3 – UDP	Urea Deep Placement for precision nitrogen management in irrigated rice	Life-cycle GWP factor: −31%; yield: +21% (from Islam et al. [20])	Reduced N_2O from volatilization and denitrification; reduced CH_4 indirectly via improved root zone conditions	Average −4.5% GHG emissions; +5.42% yield over 2026–2040 vs. S1
S4 – Mechanization	Progressive substitution of carabao with mechanical tillage equipment	Carabao enteric + manure emission factor reduced proportionally to mechanization rate	Elimination of enteric fermentation and manure-related CH_4 from carabao	Average −0.2% GHG emissions; negligible yield change over 2026–2040 vs. S1

AWD = Alternate Wetting and Drying; UDP = Urea Deep Placement; GWP = Global Warming Potential. All percentage reductions represent averages over the full 14-year simulation period (2026–2040) relative to **Scenario 1.**

Scenario 1 (Base Scenario): Traditional Water Management: In the base scenario, farmers follow the typical rice cultivation practices and use traditional water management techniques without any additional mitigation strategies to reduce GHG emissions. The GHG emissions from the base scenario will serve as a basis of comparison for the various mitigation techniques studied. The baseline assumes that, as of 2026, no irrigated rice areas have adopted AWD, biochar, or UDP, consistent with PSA [17] data indicating that these practices had negligible national adoption at the start of the simulation period. Emissions in the base scenario are mainly in the form of CH_4 due to the continuous flooding of rice paddies creating anaerobic conditions suitable for CH_4 production. Emissions from soil cultivation and other agricultural activities were sourced from various studies.

Scenario 2. AWD with Biochar Application (Based on Yagi et al.)(18)

AWD practices for flooded rice involve periodically allowing the soil to dry to a certain depth before reflooding. By allowing short periods of aeration in flooded soils to prevent methanogenesis, AWD has been shown to reduce CH_4 emissions in flooded rice systems by up to 35% [18]. Biochar has also been shown to reduce CH_4 and N_2O emissions from agricultural soils, of approximately 20% on average [19]. Biochar can also increase crop yields by improving the ability of soils to retain water and by promoting beneficial microbial activity with increases in crop yield of up to 28% on average [19]. In this work AWD practices are restricted to flooded irrigated fields where the farmer has control of the water supply. These practices are not applied to

rainfed or transiently flooded systems. A single factor, the combined AWD–biochar emission reduction factor, has been calculated to represent the combined CH_4 suppressive effects of both AWD and biochar by virtue of partially shared mechanisms.

In these scenarios the adoption dynamics of AWD and biochar for rice are modeled to switch to the respective scenarios in 2026. In the following years the respective functions for the irrigated rice area are to increase towards 40% by 2035 at a maximum, as there are constraints to adoption (e.g. required infrastructure, reach of extension services, farmer incentives) for both practices. For AWD control of irrigation is needed for flooded paddies, for biochar production feedstock is needed. 40% is thus the ceiling for these functions, increasing from 0% in 2025, avoidance of soil cultivation. Bautista et al. developed this baseline 35% reduction credit applies.

Scenario 4: Gradual Mechanization of Rice Fields (Based on Bautista et al.)(8). Scenario 4 models the progressive replacement of carabao (water buffalo) with mechanical tillage equipment. Carabao contribute to on-farm GHG emissions through enteric fermentation (CH_4) and manure management under flooded conditions. Emission factors from Bautista et al. [8] were used to parameterize carabao-related emissions. This scenario does not include embodied emissions from machinery manufacturing or fossil fuel combustion during mechanized field operations; the exclusion of these upstream and fuel-use emissions is acknowledged as a limitation that may cause the model to overestimate the net GHG reduction from mechanization.

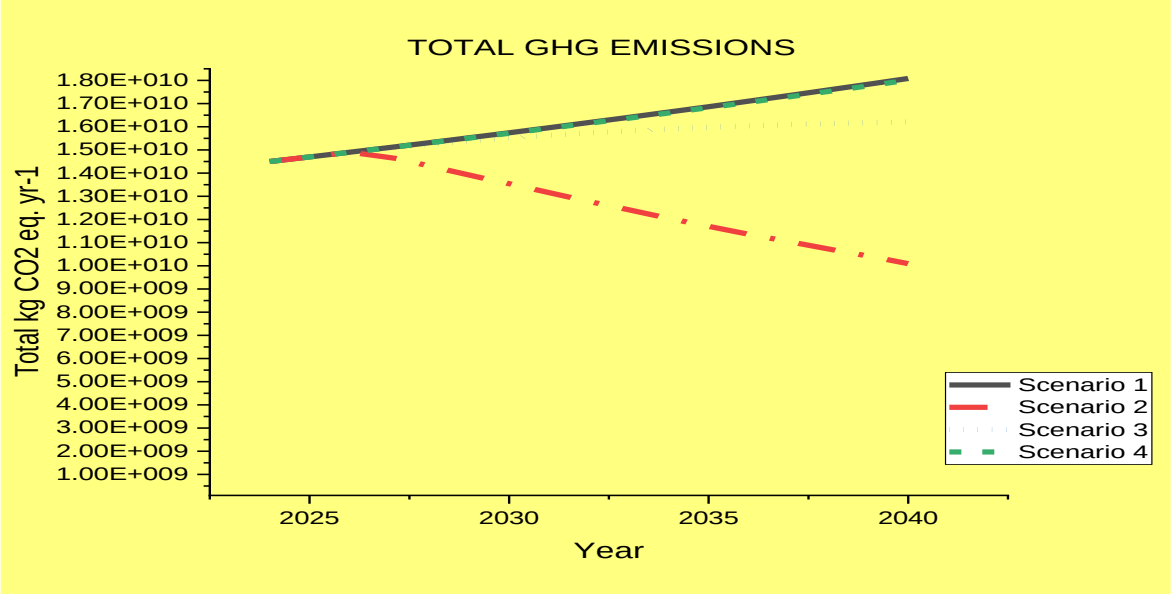


Figure 3. Total GHG Emission in Rice Production

3.2 GHG Emissions from Rice Production

Total GHG emissions were estimated using the following formula:

Total GHG Emissions = (Emission Factor for Non-Irrigated Rice × Total Area for Non-Irrigated Rice) + (Emission Factor for Irrigated Rice × Total Area for Irrigated Rice) (1)

Under the baseline scenario (Scenario 1), total national GHG emissions from rice production are estimated at approximately 15.11 Tg CO_2eq yr^{-1} in 2026, based on the emission factors from Bautista et al. [8] and the harvested areas in Table 1 [(3,920 kg CO_2eq ha^{-1} yr^{-1} × 3,340,000 ha) + (1,380 kg CO_2eq ha^{-1} yr^{-1} × 1,460,000 ha) = 15,107,600,000 kg CO_2eq yr^{-1}]. This formula multiplies the Emission Factor of rice cultivation from Bautista et al. [8] by the Rice Harvested Area of Philippine provinces from the Philippine Statistics Authority (PSA). The Emission Factor is the average emission per unit area of rice cultivation given in kg CO_2eq./ha/yr. It includes the emissions of CH_4 from flooded paddies, N_2O from fertilizers, and CO_2 from soils and other sources. The Rice Harvested Area is the area actually harvested of rice in hectares. This is the key variable in determining emissions, as it is the scale of rice production in the country. The larger the area harvested, the larger the emissions from rice cultivation.

For the four scenarios, Figure 3 displays the annual total GHG emissions for the years 2026 to 2040. Scenario 2 showed the biggest decrease in total GHG emissions with an average reduction of 23–27% below Scenario 1, with highest reduction in CH_4 production due to AWD. In addition, biochar had a further effect on the emissions, especially by influencing methanogenesis and nitrification. The difference in emissions between Scenario 2 and Scenario 1 was however smallest at the beginning because of the slow introduction of rice into the farms. It increased with time and reached a ceiling approximately between 2032 and 2033 years.

The average annual emissions for Scenario 3 is 4.5% reduction lower than the average annual emissions for the Scenario 1 baseline with a range of 4% to 5% reduction in GHG emissions for the four 5 year simulation periods. The nitrogen use efficiency intervention UDP for Scenario 3 reduced the emissions of N_2O as well as the emissions of CH_4 on an indirect basis by reducing methanogenesis in the presence of high reduced N compounds especially when the amounts of these N compounds exceed the soil N holding capacity. The amount of emissions reduced in this Scenario is much smaller compared to Scenario 2.

Average annual emission reduction for Scenario 4 was less than one percent averaging 0.2% (range 0.2% to 0.3%) throughout the study period. Since contribution of emissions from carabao enteric and manure sources were relatively low compared to other emission sources of Philippine rice such as paddy methane and fertilizer derived N_2O, results indicated that implementing mechanization in rice farming would not bring about significant emission reduction and that focuses should be on water management and fertilizer efficiency.

3.3 Effects of Mitigation Strategies on Rice Production

On the average, there was a 6.81% yield gain over a 14 year period in Scenario 2 (Fig. 4). Much of these yield gains came from areas where AWD technologies were implemented to improve water management. AWD irrigation is known to reduce GHG emissions, increase water use efficiency and to improve physiological rice yields. Periods of intermittent drying also improve soil aeration that in turn improve root growth and nutrient acquisition thus promoting greater rice plant health and drought tolerance. These large yield gains from sustainable environmental practices are "win-win" for the environment and the farmers.

In Scenario 3, average gains of 5.42% rice yield were achieved. The use of UDP to improve N-use efficiency by placing urea in the soil profile in a location amendable to crop uptake significantly reduced potential losses of N to the environment through volatilization, denitrification, and leaching. Although Scenario 3 gain was less than that found in Scenario 2, considerable agronomic benefits were derived from improved nitrogen management with reduced emissions of N_2O without loss of crop yield.

The results for Scenario 4 (mechanization) indicate that replacing animal-powered tillage with mechanized equipment does not produce meaningful increases in rice yields. In order to understand why, it is necessary to understand what is meant by mechanization of rice cultivation. Efficiency of cultivation and methane emission from animal sources may be reduced, but these are not the same as increasing crop growth or increasing efficiency of use of inputs. There are strong biological reasons why simply increasing the scale or intensity of the current rice production system is unlikely to result in significant yield increases, even though there are some technologies and practices that could help to increase yields of rice and other crops, such as improvement of water and nutrient supply, and of plant health.

3.4 Yield-Scaled GHG Emissions (Emission Intensity)

To provide a more complete picture of scenario performance, yield-scaled GHG emissions—expressed as kg CO2e per tonne of rice produced—were calculated for each scenario at the end of the simulation period (2040). These values reflect the GHG efficiency of rice production rather than total emission volumes.

Table 4. Projected Scenario Outcomes and Yield-Scaled Emissions at 2040 (Revised)

Scenario	Avg. GHG Reduction vs. S1	Avg. Yield Gain vs. S1	Ranking (GHG Reduction)	Ranking (Yield Gain)
S1 – Baseline	— (reference)	— (reference)	4th	4th
S2 – AWD + Biochar	25% (range: 23–27%)	+6.81% (range: 5–8%)	1st	1st
S3 – UDP	4.5% (range: 4–5%)	+5.42% (range: 4–6%)	2nd	2nd
S4 – Mechanization	0.2% (range: 0.2–0.3%)	Negligible (<0.5%)	3rd	3rd

All values represent averages across the full 14-year simulation period (2026–2040) relative to Scenario 1. Ranges derived from one-at-a-time sensitivity analysis (±20% on key emission and yield parameters).

Scenario 2 reduces both total GHG emissions and emissions per unit of rice produced because yield gains outpace any production-induced emission increase. Scenario 3 similarly improves emission intensity through yield gains achieved with reduced nitrogen losses. In contrast, Scenario 4 neither substantially reduces total emissions nor increases yield, resulting in negligible change in emissions intensity. These findings support prioritizing Scenarios 2 and 3 in policy design.

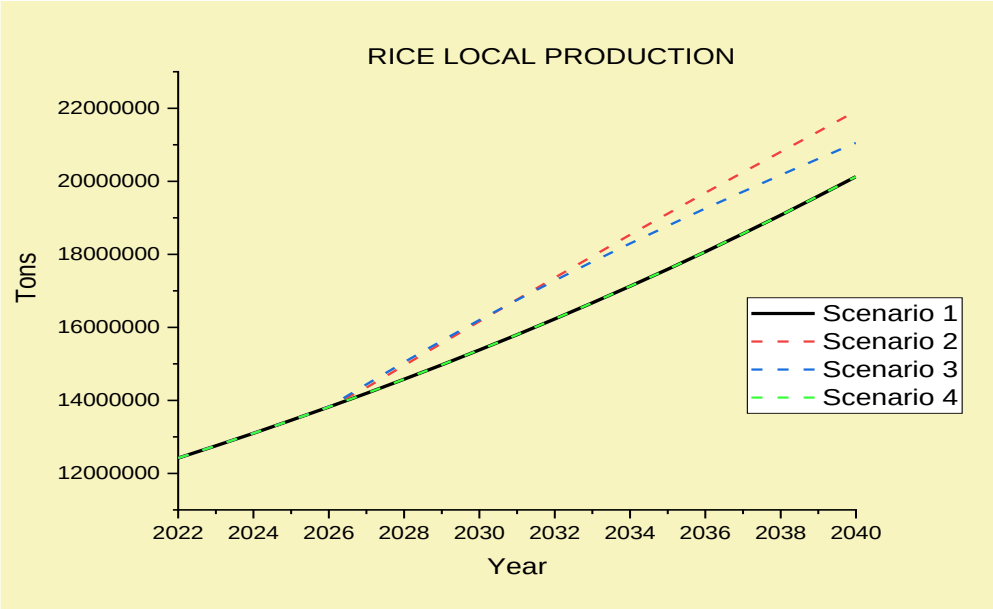


Figure 4. Local Rice Production in the Philippines with Scenarios

3.5 Policy Recommendations

3.5.1 Policy 1 – National Program for AWD and Biochar Application

Scenario 2 (AWD with Biochar Application) demonstrated the highest simulated percentage decrease in total GHG emissions (25%) and increase in rice yield (6.81%) among all scenarios compared. For Scenario 2 to be effectively implemented at the national level, several enabling conditions or interventions must be put in place. First, tertiary level irrigation infrastructure must be invested by farmers in order to control water for effective AWD implementation. Biochar production facilities must be established at the barangay or municipal level using agricultural residues such as rice husk for field application. The Department of Agriculture must invest capital for biochar production through existing rural credit programs in the Department. Farmer Field Schools (FFS) must be updated to include AWD scheduling, monitoring of field tube water levels, production of biochar, and rates of biochar application. Seed systems for rice must be supported for the production and dissemination of suitable rice varieties that can grow well under AWD conditions of low water in the field. These interventions can be made by the National Irrigation Administration (NIA) and Philippine Rice Research Institute (PhilRice) with required budget from Rice Competitiveness Enhancement Fund (RCEF) or Philippine Green Job program to subsidize farmers.

3.5.2 Policy 2 – National Strategy for Nitrogen Management through UDP

Results for Scenario 3 also show promising reduction of GHG emissions in rice production for the country. In terms of percentage change, Scenario 3 showed reduction of emissions for about 4.5% while an increase of 5.42% in production of rice was also observed. These results could be better addressed by UDP (Urea Deep Placement) or by UDP combined with LP (Low Application Rate). In cases where AWD (Alternate Wetting and Drying) of rice fields is not very feasible such as in rainfed areas, UDP would be the better strategy to mitigate climate change in rice production. UDP and LP could be incorporated into the fertilizer subsidy program of the Department of the Department of Agriculture by subsidizing or co-investing for the UDP applicator. UDP could also be a component of the seed-fertilizer package promoted by PhilRice through Farmer Field Schools. Fertilizer package promoted by PhilRice through Seed-Fertilizer Package demonstrations in different regions of the country could also incorporate UDP practices. Pre-formed urea briquettes or supergranules could also be sold by fertilizer distributors and farmers' cooperatives in different villages throughout the country.

A formal cost-benefit analysis is beyond the scope of this study. However, based on published implementation costs, AWD requires irrigation control infrastructure—a low cost per hectare in areas with existing tertiary canals primarily, while biochar requires local feedstock processing equipment. UDP applicators are low-cost, commercially available hand tools. A future study incorporating economic data from the Department of Agriculture would allow a cost-effectiveness ranking of these interventions per unit of GHG reduction achieved.

3.5.3 Implementation Barriers and Enabling Conditions

In Scenario 4, the emissions from carabao are a very small percentage of total SD emissions from rice production. Thus, mechanization should not be developed and implemented as a strategy to mitigate climate change. However, there are many benefits that it can bring to farmers, including increased labor productivity and earlier timing of farm operations. If these benefits are achieved, there would be some co-benefits to climate change but these would have to be combined with the adoption of AWD or UDP for there to be any meaningful mitigation of climate change.

All the scenarios are developed under the same set of assumptions regarding the increase in adoption of different rice production practices. These practices need specific infrastructure, training and financial support. Field implementation programs of mitigation practices for climate change should consider the same set of adoption barriers when designing their respective monitoring and evaluation frameworks. Annual reporting of areas under AWD and rate of biochar application through Department of Agriculture's Agricultural Indicators System (AIS) can help monitor the emission reduction achieved through the different practices for adaptive management.

4. Limitations

There are several limitations to this study that must be noted. The emission factors used in this study to calculate the GHG emissions from the different rice production practices in the Philippines were derived from Bautista et al. [8] that was published in 2005. It is therefore possible that the study may not capture the current scenario of rice production in the country. Changes in cultivars used, in irrigation systems, and in the fertilizer management practices of farmers may have affected the emission factors for each of the different rice production practices. The use of updated emission factors for each of the different rice production practices in the country would improve the accuracy of accuracy of the model in estimating the GHG emissions from the different rice production practices in the country. In addition, the model is a national model and does not take into account the large variations that exist in the country in terms of soil type, water management practices, cropping intensity, and climate. Therefore, future studies must incorporate a regional perspective to improve the applicability of the model to different regions of the country.

Another important point to mention is that the study only evaluated Scenarios 2 and 3 separately instead of their combined evaluation to identify the most effective integrated strategy for addressing rice climate change mitigation. These two scenarios respectively address two sets of different emission-reduction mechanisms that a farmer and thus the policy can address cumulatively. An integrated SD scenario (Scenario 5)

that combines all of the above mitigation mechanisms that can be implemented by a farmer would likely perform better than either of the Scenarios 2 or 3. The study will address this in future evaluation of integrated SD scenarios for reducing rice climate change mitigation.

5. Conclusions

A system dynamics approach was used in formulating a model to predict potential Greenhouse Gas (GHG) emissions from rice production in the Philippines over a 14-year period (2026–2040). Four different scenarios were explored and the potential effects thereof were discussed. Good accuracy was obtained in all the validation variables with the highest mean absolute percentage error (MAPE) of 1.52%. Among the developed scenarios, the second one (Scenario 2), based on combined AWD and biochar application to rice crop, emerges as the most effective option. The average reduction in global warming potentials was 25% (range: 23–27%) over Scenarion 1 (baseline) and average yield gain was 6.81% (range: 5–8%). This approach solves two problems of rice farmers by conserving water and improving soil health. Scenario 3 (UDP), based on optimization of N application achieved 4.5% (range: 4–5%) reduction in GHG emissions and 5.42% (range: 4–6%) gain in crop yield. On the other hand, Scenario 4, which is mainly based on mechanization has no gain in crop yield and achieved very small reduction in GHG emissions i.e. 0.2% (range: 0.2–0.3%) only and hence is not a preferred option.

Scenarios 2 and 3, evaluating AWD with biochar and UDP respectively, represent the most effective simulated options for reducing GHG emissions from rice production in the Philippines. A combined integrated scenario was not explicitly modeled in this study; however, the complementary emission-reduction mechanisms of AWD, biochar, and UDP suggest that their combined application is a promising direction for future research and policy design. This innovation for rice-based ecosystems is highly relevant to the Philippines' Nationally Determined Contributions (NDCs) under the Paris Agreement. It will empower millions of small scale farmers to improve their livelihoods in a resilient and sustainable manner. In the long term, the three technologies can help enhance climate resilience, soil health and water-use efficiency through well-designed policies such as investment support, rural infrastructure, awareness creation and mainstreaming into national plans on climate change and agriculture.

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