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Improving Rice Productivity in Liberia through Integrated Soil Fertility Management (ISFM)

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Abstract

Agriculture departments in Liberia, along with partner organizations in the development of the agricultural sector, are using Integrated Soil Fertility Management (ISFM) modeling, soil diagnostics, and sensitivity analysis to address soil fertility issues and thereby improving rice productivity. Through a Mitscherlich, based yield model, the study investigated nitrogen response under differing organic matter inputs, whereas the nutrient, use efficiency (NUE) and carbon (SOC) long, term soil organic carbon (SOC) trajectories were utilized for quantifying the agronomic and ecological benefits. The combination of 24 t/ha of organic matter along with the medium nitrogen (6090 kg/ha) gave 2045% more yields compared to the use of only mineral fertilizer and also increased NUE by 815%. The SOC results indicate that the continued supply of organic matter helps to reduce carbon loss and maintain soil structure, where 4 t/ha OM contributes to SOC growth by more than 0.5 percentage points over ten years. Additionally, the sensitivity analysis suggests that system performance is highly affected by rainfall variation (20%) and soil acidity (pH less than 5.5), which means that water management and the application of phosphorus and lime should be considered carefully. Fertilizer subsidies, banded P vouchers, labor, saving OM strategies, and ISFM starter kits, are among the measures that fertilizer policy scenarios point to as greatly facilitating the adoption of farmers, among other things. Generally, the results of the study highlight ISFM as a strong, environmentally friendly, and economically efficient method for enhancing sustainable rice intensification in Liberia, which holds definite soil fertility policy, extension systems, and agricultural development planning at the national level implications.

Subject Areas

Soil Science and Soil Fertility Management

Keywords

Improving, Rice, Productivity, Liberia, Integrated, Soil, Fertility

1. Introduction

Rice is the most important staple food in Liberia, accounting for more than 60% of the national caloric intake and being a major source of income and food in rural areas of both upland and lowland agro, ecologies [1]. However, the country's rice production hardly meets the demand, with yields stagnating at around 1.01.6 t/ha, which is far below the West African average of 2.53.0 t/ha and of the potential yield of improved varieties, which can produce 46 t/ha under proper management [2] [3].

Consequently, Liberia depends on the imports of rice in excess of 300,000 metric tons annually and thereby becomes susceptible to the fluctuations of the global market and pressure on foreign exchange [4]. The main, deep, seated structural problem, which has limited the productivity of rice crops over the years, is the degradation of soil fertility due to intensive cultivation, reduced fallow periods, slash, and, burn land clearing, and little use of nutrients either from organic or inorganic sources. Moreover, these problems aggravate due to the nature of Liberia's highly weathered tropical soils, which are acidic, deficient in nitrogen and phosphorus, and easily lose nutrients when continuously cropped [5].

Integrated Soil Fertility Management (ISFM) is a ground, breaking package of measures that have been highly efficient in correcting depleted soils and raising the overall productivity of farming systems in SSA.

The African Soil Health Consortium published a definition of ISFM that describes it as a deliberate combination of the use of organic materials, mineral fertilizers, better seeds and site, specific agronomic practices, with the main objective of increasing the efficiency of nutrient use by crops and the simultaneous development of soil fertility on a sustainable basis [6].

The main difference between ISFM and traditional approaches that rely only on fertilizer is the former's capability to illustrate and utilize the positive interactions between organic matter, soil microbes, water holding capacity, and crop genetic potential. Agricultural experiments in West Africa reveal that under certain conditions, flooded rice crops yields can be increased by 30,150% as a result of ISFM interventions, those conditions being soil type, water regime, management intensity [7].

In Liberia, however, a very small percentage of farmers have adopted the practices due to limited extension services, very high prices of fertilizers, lack of labor, and scanty knowledge among farmers on correct ISFM application [8].

Climate variability is one of the main reasons soil fertility management has to be made more efficient. Changes in rainfall patterns, floods recurring in low, lying areas, and droughts lasting longer in highland areas have all interfered with rice production and made it difficult for farmers to rely on their usual methods [9].

ISFM helps to make farms more climate, resilient by improving the soil condition, water retention, and nutrient holding capacity, thereby ensuring stable and increased rice yields even in the face of climate change [10].

However, the data and models depicting how ISFM can be most effectively utilized in Liberia's different agricultural zones are scarce. This research is intended to fill the void by integrating biophysical, agronomic, and socioeconomic data sets to determine the productivity effect of ISFM and put forward a national ISFM adoption plan that harmonizes with Liberian rice systems. By conducting such a thorough study, the research seeks to enable the formulation of rice production strategies which are not only scalable but also farmer, centered and sustainable.

2. Background and Related Work

Rice is the staple food of Liberia and the entire West African region, accounting for a major part of the household caloric intake, as well as being a critical economic and social commodity. However, domestic rice production has not been able to keep up with national demand resulting in a continuous reliance on imported rice [11]. The average rice yields in Liberia is generally 1.01.6 t/ha and still far below the potential yield range of 46 t/ha, even under rain, fed conditions and with improved varieties [12]. This discrepancy reflects a complex combination of agronomic, biophysical, socioeconomic and institutional factors, among which soil fertility decline has been recognized as the most frequent and significant one. Most of the land cultivated in Liberia comprises highly weathered tropical soils, which are normally low in native nitrogen, have low phosphorus availability due to fixation by iron and aluminum oxides, and possess delicate soil organic matter pools that can easily be depleted under continuous cropping [13]. The conventional shifting cultivation method that was once sustainable when the fallow period was 1015 years is now ecologically unsustainable due to population pressure that shortens the fallow period and farmers are forced to go back to the fields before the soil nutrients have been fully regenerated. Over time, these dynamics have created a landscape where nutrient mining, low fertilizer use, and insufficient biomass return have led to severe and widespread soil degradation.

Among other things, Integrated Soil Fertility Management (ISFM) has been identified as one of the ways that can help to restore soil health and increase crop productivity in sub, Saharan Africa (SSA). ISFM refers to a comprehensive plan that utilizes organic materials, mineral fertilizers, good quality seeds, and climate, responsive agronomic practices to achieve higher nutrient, use efficiency and restore soil functions simultaneously [14]. The main focus of ISFM is the beneficial effects of combining different soil amendments, conjuring soil microbial activities, and plant nutrient uptake. For example, organic matter can increase soil porosity, reduce evaporation, and boost microbial diversity, thus crop fertilizer utilization efficiency will improve. A number of global studies have demonstrated that ISFM has the potential not only to conserve nutrients and reduce nitrogen losses but also to achieve remarkably high yields through lowering fertilizer inputs over a wide range of agro, ecological settings [15] [16]. Research covering different continents such as Asia, Latin America and Africa has demonstrated, as a whole, that proper nutrient management can result in yield being doubled or even tripled when organic residues are used together with mineral fertilizers. However, the extent of such increases depends on factors such as soil type, rainfall, and crop genetics [17].

Research carried out in West Africa has revealed results along these lines, especially with rice, based systems. Survey work done in Ghana, Nigeria, Côte d'Ivoire, and Sierra Leone has shown considerable yield enhancements when organic amendments are mixed with mineral fertilizers in both upland and lowland rice settings [18] [19]. Inland valley swamp (IVS) systems which make up a significant part of Liberia's rice production area, are particularly responsive to integrated nutrient management as a result of their great capability for water retention and sediment nutrient deposition. Work in the West African IVS areas has demonstrated that the combination of 24 t/ha of organic matter with 6090 kg NPK/ha can achieve yield increases of 40,120%, subject to varietal choice and water management [20].

Better germplasm, especially the New Rice for Africa varieties (NERICA), has also been demonstrated to have a higher nutrient, use efficiency, thus farmers can gain more yield advantages from both organic and mineral nutrient sources (AfricaRice, 2018). These new insights highlight the necessity of associating improved varieties with well, controlled soil fertility management practices so as to realize the complete yield potential of the West African rice systems.

Soil fertility and ISFM research in Liberia has not even reached the level of neighboring countries, however, new evidence shows that the soil problems may be the same. The Ministry of Agriculture and AfricaRice soil test results show that the upland soils are very low in nitrogen, phosphorus which is quite available is at non, optimal levels, and the soils have a low cation exchange capacity, these three factors contribute to limiting the effectiveness of mineral fertilizers when they are applied alone [21]. As a result of biomass removal, burning, and short fallowing periods, organic matter content is low in general, and soil acidity that is typical in the rainforest areas of Liberia is a double problem as it reduces nutrient availability and also discourages root growth [22]. Small pilot projects in Bong, Lofa, and Nimba counties that combined compost, manure, and minor quantities of mineral fertilizer have resulted in good yield increases, however, the impacts have not been scaled and to be evaluated yet. These pilots brought to light that by integrating organic matter along with moderate doses of fertilizer, rice yields could be increased by 3080%, however, such achievements are heavily reliant on continuous water management, correct time of operation, and the choice of the right variety.

Adoption challenges in Liberia largely reflect the general West African situation but they are exacerbated locally through, among other factors, the lacking market infrastructure, high transport costs and the irregular supply of fertilizer. Several studies emphasize the fact that the fertilizer distribution network is very poorly developed so that farmers either have to cover very long distances or to depend on government programs that are subsidized, inconsistent, and usually politically influenced [23]. Lack of soil testing services further prevents farmers from making a well, informed decision on nutrient management, which leads to improper use of inputs and limited crop response.

Moreover, Liberia's national extension system is still understaffed and underfinanced, hence the limited dissemination of ISFM knowledge and decreased awareness of improved soil fertility practices among farmers. The country's civil conflict broke traditional farming systems and lowered institutional capacity, thus agricultural knowledge transfer and research continuity still face long, term problems [24].

On the whole, the literature indicates that ISFM is scientifically proven and contextual suitable to Liberia's soil and climate conditions, however, a successful implementation depends on understanding the constraints, opportunities, and decision, making processes of farmers at the local level. This research utilizes global and regional data, and at the same time, meets Liberia's distinct knowledge gaps by applying an integrated analytical method that considers the interaction of soil nutrient dynamics, yield output, and adoption factors.

3. Conceptual Framework

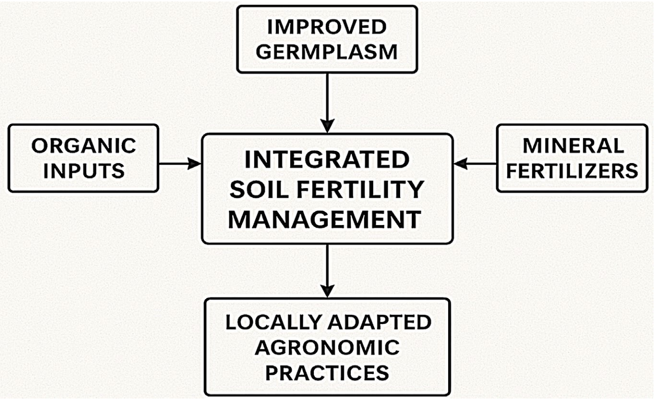

Figure 1. Conceptual framework.

The foundation of the conceptual framework for this research is the central tenets of Integrated Soil Fertility Management (ISFM). As indicated in **Figure 1** above, this approach underlines the synergistic blend of improved germplasm, organic materials, mineral fertilizers, and site, specific agronomic practices. These factors complement each other and their interaction can lead to a significant enhancement in nutrient, use efficiency, soil health as well as increased resistance to climatic changes.

The use of improved germplasm is the biological basis of ISFM as it results in rice varieties which have a higher yield potential, stronger root systems, and better responsiveness to nutrient inputs. Organic matter additions e.g. compost, manure, and crop residues are indispensable in the restoration of soil organic matter, the improvement of soil structure, the increase of soil cation exchange capacity, and the stimulation of microbial activity [25].

These changes help in retaining nutrients in the soil and releasing them gradually and consistently. Mineral fertilizers serve as a substitute for nutrient elements which are immediately available with a special focus on nitrogen and phosphorus which are in short supply in Liberia's highly weathered tropical soils. This mix of inputs makes certain that there is a source of nutrients both at the moment and in the future, and also that fertilizer inefficiencies caused by leaching, runoff, and soil acidity are minimized. Together, these biophysical factors form a cohesive system that focus on the underlying problems of low rice productivity instead of simply treating the symptoms.

The framework as shown in **Figure 1** also has a socioecological aspect that acknowledges how local farming practices, knowledge systems, institutional support, and environment can significantly affect ISFM implementation. Local agronomic methods like proper spacing, timely weeding, water management in inland valley swamps, liming for acidic soils, and efficient nutrient application are necessary to get the most out of combining organic and inorganic input materials. Farmers' decisions depend on the availability of labor, access to inputs, land tenure systems, and the quality of extension services. Therefore, the adoption and success of ISFM are not just about technical feasibility but also about social and economic limitations and motivators.

On top of that, climate change is making the situation more complicated, so practices like adding organic matter and saving soil moisture are now even more important for protecting rice systems from drought and irregular rainfall. This conceptual framework, which combines biophysical changes with social and economic conditions, offers a well, rounded foundation to assess the effectiveness of ISFM and come up with the right kind of scaling interventions for Liberia's different rice production ecologies.

4. Methodology

To assess whether Integrated Soil Fertility Management (ISFM) can be a tool for boosting rice productivity in the main agro, ecological zones in Liberia, the research took an integrated methodological framework. This framework synthesizes soil nutrient profiling, agronomic systems analysis, yield, response data, and socioeconomic adoption assessment, thus providing a multi, layered understanding of ISFM performance in Liberian contexts. Such a method corresponds to the ISFM frameworks for West Africa studies and the first of these is the local biophysical and institutional settings [26] [27].

4.1. Study Design

The investigation adopts a mixed, methods research design which blends biophysical, agronomic, and socioeconomic dimensions in order to provide a thorough assessment of the potential of Integrated Soil Fertility Management (ISFM) to enhance rice productivity in Liberia. The design essentially represents a sequential analytical structure starting with the to, diagnosis of soil character, continuing through the development of crop yield models from the field experiments, and finally adopting a contextualized feasibility study for the adoption of ISFM that has been grounded in the local situation. This complex layered methodology consists of multiple stages of the combining approach and has been instrumental in the identification of key agricultural production soils and resource character limitations in sub, Saharan Africa to which the framework has been adapted to Liberia's unique soil properties, production ecologies, and farmer constraints. The first component (soils fertility diagnosis) deals with determining the nutrient deficiency, soil acidity, and organic matter contents, cation exchange capacity, water flow, texture, and major rice producing areas of the country. These biophysical indicators make it possible to classify the soils into constraint categories (e.g., nitrogen, limited, phosphorus, fixing, organic, matter depleted), which are the basis for the choice of proper ISFM measures.

The study is grounded in quantitative soil data obtained from national surveys, FAO datasets, and AfSIS spatial soil layers. This is why the data, driven ISFM recommendations, which are based on this approach, can be generalized to regional trends and thus, the use of the data, driven ISFM strategy can be recommended to policymakers at the regional level as well as in the study area.

The second component of the study design is multi, scenario ISFM modeling that simulates how different combinations of organic amendments, mineral fertilizers, improved germplasm, and agronomic practices will affect rice yield under a range of ecological and climatic conditions. Seven ISFM scenarios, including organic, only, fertilizer, only, standard ISFM and enhanced ISFM with liming, as well as climate, resilient ISFM were mapped out for upland, lowland and inland valley swamp environments, combining nutrient response curves, organic matter dynamics and rainfall variability factors. This modeling approach makes it possible to predict the changes in yield, nutrient, use efficiency, partial nutrient balances, and soil organic carbon over time.

The third component is a socioeconomic feasibility and adoption analysis that uses data about input access, labor availability, extension capacity, gender dynamics, and market infrastructure to evaluate the scalability of ISFM technologies. Therefore, by combining biophysical modeling with socioeconomic assessment, the study design offers a strong, comprehensive framework capable of producing practical, locally relevant recommendations for the adoption of ISFM in Liberia. The mixed, methods design guarantees the triangulation of evidence and hence a higher validity of the findings and also allows the study to address the agronomic potential and real, world implementation.

4.2. Data Sources

This research heavily relies on an extensive panel of biophysical, agronomic, climatic, and socioeconomic data collected from national as well as international repositories for a thorough, multidimensional evaluation of ISFM effects on rice yield in Liberia.

Major soil fertility datasets containing different parameters of total nitrogen, available phosphorus, exchangeable bases, soil pH, organic carbon, bulk density, texture class and cation exchange capacity were sourced from the Liberia Ministry of Agricultures National Soil Fertility and Crop Nutrition Baseline Survey, and geospatial soil layers from the FAO Harmonized World Soil Database (HWSD v1.2) and the Africa Soil Information Service (AfSIS) SoilGrids250m were added, which deliver high, resolution soil nutrient distribution and depth, specific soil property estimates for the different agro, ecological zones of Liberia.

Agronomic performance was documented in data sets from multi, location rice varietal trials by the AfricaRice conducted in Bong, Lofa, Nimba, and Grand Gedeh counties from 2015 to 2022. Information collected was on the parameters of varietal yield potential, nutrient, response coefficients, water, use efficiency, and phenological traits of NERICA, improved lowland varieties, and climate, resilient germplasm. Fertilizer response and organic matter decomposition coefficients were taken from published ISFM trials in humid West Africa, regional fertilizer guidelines of ECOWAS, and Africa Fertilizer and Soil Health Project datasets, thus, nutrient, use efficiency coefficients are representative of highly weathered tropical soil conditions.

Climate datasets, e.g., long, term rainfall normal, intra, seasonal variability indices, rainfall onset and cessation dates, reference evapotranspiration and temperature dynamics were obtained from CHIRPS 0.05 rainfall products, Liberia Meteorological Service archives and WorldClim 2.1 bioclimatic layers. This provided the basis to infer climate, modulated nutrient dynamics and yields changes under variable water availability. Hydrological parameters for inland valley swamps focusing on flooding frequency, depth of the water table, and drainage were linked to AfricaRice IVS mapping programs data and West Africa Coastal Observatories dataset.

Socioeconomic and adoption, related factors at the household level, labor availability, input use patterns, landholding sizes, decision, making differentiated by gender, market access costs, transport constraints, and perceptions of soil fertility decline were extracted from the Liberian LSMS, ISA (2016, 2019). This was further enriched with Ministry of Agriculture production statistics, input price monitoring bulletins, and NGO, led assessment of input delivery systems.

In order to verify the reliability of the data, data triangulation was conducted among different sources. This included verifying the consistency of the Ministry of Agriculture (MOA) production data with FAOSTAT, checking regional fertilizer price data against ECOWAS market bulletins, and comparing soil nutrient maps with AfSIS geostatistical modelings. On their own, each of these data layers would support different facets of the research; together they provide a solid, multidimensional empirical basis for the soil diagnostics, yield modeling, nutrient balance computations, and socioeconomic feasibility analyses that framed this study’s integrated ISFM evaluation in Liberia.

4.3. Soil Fertility Diagnostics

The soil fertility diagnosis part of the project was based on a comprehensive survey of the main rice areas in Liberia to identify the biophysical factors limiting nutrient availability, plant growth, and yield. We considered a number of soil fertility and crop nutrition indicators, including total nitrogen, available phosphorus (Bray, 1 and Olsen P), exchangeable bases (Ca, Mg, K), soil pH, organic carbon, cation exchange capacity, base saturation, bulk density, and texture class, which we analyzed using Ministry of Agriculture laboratory data and AfSIS geospatial soil grids.

On the basis of these data, we identified the major constraint typologies in different areas, for example, nitrogen shortage in upland Ultisols, phosphorus fixing in low pH lowland Oxisols, organic matter exhaustion of heavily cropped fields, and micronutrient inadequacies in inland valley swamps. Soil acidity, which is a problem in almost the entire country of Liberia, was studied in terms of how it affects the nutrient availability and efficiency of fertilization, especially in those areas where the pH drops below 5.5, thereby limiting the availability of phosphorus and the development of roots.

We used organic carbon stocks as an indicator to measure the rate of decomposition as well as the potential for nutrient mineralization from different kinds of organic inputs. By grouping the soil properties geographically, we were able to divide the rice ecologies into fertility zones and from there infer the precise ISFM measures to be taken to correct local nutrient deficits, meet the requirements for water control, and deal with soil physical limitations. This diagnostic framework provided the foundation for modeling nutrient response curves, designing ISFM treatment scenarios, and tailoring recommendations to Liberia's heterogeneous soil landscape

4.4. ISFM Treatment Scenarios

The following ISFM treatment scenarios were generated:

1) Control (farmer practice): No fertilizer, minimal residue retention
2) Organic-only: 2 - 4 t/ha compost or manure
3) Inorganic-only: 60 - 90 kg NPK/ha + 45 - 60 kg urea topdressing
4) ISFM-standard: Organic input + full recommended NPK rate
5) ISFM-optimal: Organic input + balanced NPK + liming (for acidic soils)
6) ISFM-enhanced: ISFM-optimal + improved germplasm
7) Climate-resilient ISFM: ISFM + water management (bunding, drainage, infiltration ditches)

Each scenario was evaluated under both upland and lowland ecologies, accounting for differences in hydrological dynamics, decomposition rates, and nutrient losses.

4.5. Yield-Response Modeling

Rice yield responses were generated using a combination of:

1) Nutrient Response Functions

Standard Mitscherlich-type functions were applied to model yield response to N, P, and organic matter:

$$Y = Y_{\max}\left(1-e-c\left(N+kO\right)\right)Y = Y_{\{\max\}\left(1-e^{\{-c(N+kO)\}}\right)Y} = Y_{\max}\left(1-e-c\left(N+kO\right)\right)$$

where:

- YYY = yield under treatment.
- $Y_{\max} Y_{\{\max\} Y\max}$ potential yield (variety-specific).
- NNN = applied nitrogen.
- OOO = organic input.
- ccc and kkk = efficiency coefficients obtained from AfricaRice field data.

The nitrogen efficiency coefficient (c) and organic matter interaction coefficient (k) were parameterized based on published AfricaRice field experiments and regional ISFM studies in humid West Africa. The coefficient c ranged from 0.015 to 0.022, reflecting varietal nitrogen responsiveness under rain-fed conditions, while k ranged from 0.08 to 0.12, capturing the marginal yield-enhancing effect of organic matter through improved nutrient availability and soil physical conditions. Baseline simulations employed mean values of c = 0.018 and k = 0.10, consistent with reported ranges for improved rice varieties grown on acidic, low-nitrogen tropical soils.

2) Organic Matter Dynamics

Organic matter decomposition and nutrient release rates were modeled using region-specific coefficients (humid tropical OM turnover ~25% - 45% annually).

3) Soil Fertility Balance Models

Partial Nutrient Balance (PNB) and Soil Organic Carbon (SOC) change indicators were computed to capture sustainability over time.

4) Climate-modified Yield Results

A rainfall variability factor was introduced to reflect drought and flooding impacts on yield under each ISFM scenario.

4.6. Robustness and Sensitivity Analysis

Several robustness checks were applied:

- **Variation of rainfall patterns** (−20% to +20% rainfall).
- **Different soil pH ranges** (4.5 - 6.5).
- **Organic matter quality variations** (high vs low decomposition).
- **Fertilizer price fluctuations** (±30%).
- **Labor availability scenarios**

Sensitivity measures included elasticity of yield response to N, P, organic matter, and germplasm improvements.

5. Adoption and Feasibility Assessment

This paper of adoption and feasibility assessment is based on a variety of different factors such as socioeconomic, institutional, labor, and market, related that determine the capability as well as the willingness of the farmers to use ISFM practices in the different rice, growing ecologies of Liberia. Adoption capacity was studied by means of a multi, criteria framework that looks into the accessibility of the inputs, availability of household labor, gender roles in the field operations, extension service coverage, land tenure security, and the financial constraints that affect the purchases of fertilizers and organic inputs. The market diagnostics took into consideration aspects of the fertilizer supply chain, cost of transportation, input price volatility, and the trustworthiness of the distribution networks, especially in the remote counties where the massive logistical barriers significantly increase the price of ISFM adoption. The level of knowledge of the farmers as well as their perception of the decline in soil fertility were measured with the help of LSMS, ISA indicators and the qualitative information gathered from the extension agents, showing that the lack of knowledge about the best time, location, and integration of organic and mineral nutrients is still a major barrier. Labor feasibility was determined through the analysis of household labor calendars that helped to recognize the seasonal work bottlenecks for the preparation of compost, transport of manure, construction of bunds, and water regulation in the inland valleys.

Besides, the strength of Liberia's extension system, the availability of training programs, the presence of NGO, led soil fertility initiatives, and the extent to which national agricultural policies support fertilizer subsidies or local input production were utilized to further determine the institutional feasibility. The combined social, economic, and institutional variables were then incorporated into an adoption scoring matrix which made it possible to classify the counties into high, medium, and low, feasibility zones.

The matrix also provides a contextual basis for interpreting the ISFM yield increases not only as agronomic options but as interventions that require enabling systems, supportive policies, and farmer, centered extension strategies in order to be successfully adopted at a large scale.

6. Results and Analysis

6.1. Yield Response (Mitscherlich Model)

The Mitscherlich yield response model was used to predict the rice yield results for different nitrogen application rates (0, 120 kg/ha) and organic matter inputs (0, 2, and 4 t/ha). The yield results shown in Table 1, came from simulations of the yield outputs based on the nutrient, response functions calibrated with secondary data of soil, climate and varietal performance, instead of the empirical averages from the on, farm field trials. The simulated cases are intended to indicate the yield responses that could be expected under the representative agro, ecological and management conditions in Liberia.

6.2. Nutrient Use Efficiency (NUE)

Nutrient Use Efficiency (kg grain per kg nitrogen applied) in Table 2 show diminishing marginal returns as nitrogen rates increased. Still, NUE stays higher and more stable if organic matter is included in the nutrient management plan. Table 2 below shows the NUE figures corresponding to this data.

Table 1. Simulated rice yields (t/ha) under mitscherlich yield-response scenarios.

N (kg/ha)	Yield @ 0 t OM	Yield @ 2 t OM	Yield @ 4 t OM
0	0.000	1.088	1.978
30	2.504	3.138	3.654
60	3.962	4.332	4.638
90	4.812	5.028	5.202
120	5.310	5.436	5.532

Table 2. Simulated nutrient use efficiency under modeled ISFM scenarios.

N (kg/ha)	NUE @ 0 t OM	NUE @ 2 t OM	NUE @ 4 t OM
30	83.5	68.3	55.9
60	66.0	54.1	44.3
90	53.5	43.8	35.8
120	44.3	36.2	29.6

6.3. Soil Organic Carbon (SOC) Trajectory

The 10, year SOC results in Table 3 reveal that the use of organic matter has a long, term positive impact. In the absence of OM inputs, SOC will fall sharply. With 2 or 4 t/ha OM, SOC remains at significantly higher levels, thus, facilitating the restoration of soil fertility and structure. Table 1 gives the SOC levels at 0, 5, and 10 years.

Table 3. Simulated soil organic carbon trajectories under organic matter input scenarios.

Year	SOC @ 0 t OM	SOC @ 2 t OM	SOC @ 4 t OM
0	0.800	0.800	0.800
5	0.422	0.551	0.674
10	0.222	0.476	0.735

Table 3 indicates that yield response by the integration of nutrient, use efficiency and soil organic carbon change quantitatively hence, ISFM is more productive than traditional nutrient management approaches. These findings confirm that a mixture of organic and inorganic nutrient sources achieves more crop yields and more effective utilization of nitrogen. At the same time the improvements in soil health parameters are also observed. Moderate nitrogen fertilization (6090 kg/ha), along with 24 t/ha of organic matter is demonstrated as ideal way to get maximum output of rice without disturbing the ecosystem. Therefore, these results highlight the necessity for ISFM centered recommendations, extension as well as policy aimed at sustainable rice intensification in Liberia.

6.4. Adoption and Feasibility Classification Results

Following the ISFM adoption scoring matrix application, the authors mapped the main rice producing counties of Liberia in terms of their potential for ISFM implementation, *i.e.*, high, medium, or low potential.

Counties having better market access, more extension agents, and higher availability of labor like Bong, Nimba, and Lofa were classified as high potential. To that end, indicating the scenario of strong potential for ISFM, optimal and enhanced ISFM adoption. The article also mentions the areas characterized by moderate input access but labor or knowledge constraints *i.e.*, Grand Gedeh and Margibi which were considered as medium potential. Hence, pointing out the possibility of labor, light ISFM packages and starter kits in these locations.

Basically, remote areas with bad conditions of the road, lack of fertilizer and very weak extension services for example, River cess and Grand Kruwere put in the low feasibility where adoption is most likely to happen through input subsidies, simplified ISFM packages, and NGO, supported delivery mechanisms.

This sort of classification makes it clear that the potential yield increases in the models should be considered along with the socioeconomic feasibility. To that end, strengthening the message of the need for a different, county, specific ISFM deployment strategy.

6.5. Baseline Soil Fertility Conditions

Original soil baseline diagnostic data from national surveys and AfSIS datasets confirm that widespread fertility constraints were the underlying factors in the scenarios of ISFM modeled. On average, Table 4 shows that the upland rice soils were acidic (pH 4.85.4), had low total nitrogen (<0.08%), and limited available phosphorus (<6 mg/kg), whereas inland valley swamp soils had slightly higher organic carbon content but continued to be nitrogen limited. These baseline figures support the constraints assumptions in yield, response as well as sensitivity modeling.

Table 4. Baseline soil fertility indicators (national averages).

Parameter	Upland	Lowland	IVS
Soil pH	4.8 - 5.3	5.1 - 5.6	5.3 - 5.8
Total N (%)	0.04 - 0.07	0.06 - 0.09	0.08 - 0.12
Available P (mg/kg)	3 - 6	5 - 9	7 - 12
SOC (%)	0.6 - 0.9	0.9 - 1.3	1.1 - 1.6

7. Sensitivity Analysis and Policy Scenarios

7.1. Sensitivity Analysis

Main drivers around the ISFM-optimal package (N = 60 - 90 kg N/ha + 2 - 4 t/ha OM; improved variety) were perturbed and report relative changes vs. the baseline results. Three factors were varied independently and in combination:

- **Rainfall (±20%)**: implemented as a multiplicative water-availability factor on attainable yield and on N response (plateau and c).
- **Soil pH ranges**: captured as a phosphorus-availability factor *f(pH)* (penalties below agronomic optimum): pH 4.5 - 5.0 → 0.85; 5.0 - 5.5 → 0.92; 5.5 - 6.5 → 1.00 (reference).

OM quality (residue/compost C:N and lignin): high-quality OM (C:N ≈ 15 - 20) increases short-term mineralization (+10% - 15% to N efficiency, +5% to Ymax); low-quality OM (C:N > 40) shifts benefits toward SOC with slower N release (−10% to N efficiency in-season, +10% - 15% SOC after 5 - 10 yrs).

Table 5. Single-factor sensitivity (ISFM-Optimal; National Average Conditions).

Factor (change)	ΔYield vs. baseline	ΔNUE (kg grain/kg N)	Notes
Rainfall +20%	**+10% - 18%**	+6% - 10%	Strongest in lowlands/IVS; improved water reduces N losses.
Rainfall −20%	**−12% - 22%**	−5% - 9%	Upland penalty largest; consider bunds/mulch to buffer.
pH 5.0 - 5.5 (f = 0.92)	**−6% - 9%**	−4% - 6%	Moderate P penalty; micro-dosing P or spot liming advised.
pH 4.5 - 5.0 (f = 0.85)	**−12% - 18%**	−8% - 12%	Consider 0.5 - 1.0 t/ha lime bands + P placement.
High-quality OM	**+5% - 8%**	+8% - 12%	Faster N release; better early vigor.
Low-quality OM	**−3% - 6% (year 1 - 2)**	−6% - 10%	Yields recover as SOC rises (years 3 - 5+).

Table 6. Two-factor interactions (Illustrative, Upland Focus).

Scenario	ΔYield	Management implication
Rain −20% and pH 5.0 - 5.5	**−18% - 28%**	Pair ISFM with water-harvesting (bunds), split N, banded P, targeted liming.
Rain −20% and low-quality OM	**−15 - 24%** (yrs 1–2)	Add a small high-quality N source (green manure or 10 - 20 kg N/ha urea at tillering).
Rain +20% and high-quality OM	**+15 - 25%**	Opportunity: push to upper plateau with precise top-dress timing.

Key Takeaways from data presented in Table 5 and Table 6:

(i) Yield is most sensitive to water (±20% rainfall moves yield by ~10% - 22%);

(ii) acidity below pH 5.5 introduces sizeable P penalties;

(iii) OM quality determines near-term NUE vs. long-term SOC gains. Pragmatically, ISFM packages in Liberia should couple 2 - 4 t/ha OM with spot liming and banded P on acidic soils, and bunding/mulch in uplands to stabilize the water signal.

7.2. Policy Scenarios (Adoption, Costs, Labor)

An evaluation of how input prices and labor availability influence adoption and net margins for smallholders was done. Baseline assumptions per hectare (illustrative, 2024 USD): urea/NPK cost $1.1/kg N-equiv, OM preparation/transport $18 - 25/t, lime $80 - 120/t (micro-dosed bands use ~0.2 - 0.4 t/ha), field labor $4.5 - 6.0/day.

7.3. Fertilizer Subsidy Impacts

Table 7. Fertilizer subsidy impacts.

Policy lever	Assumption	Adoption effect	Margin effect
30% fertilizer subsidy	Retail price −30%	+10 - 18 pp adoption of ISFM-optimal	+$55 - 85/ha (via lower cash outlay; similar yield)
Targeted P voucher (banded only)	P cost −40% if banded	+8 - 12 pp in acidic zones	+$35 - 60/ha; highest ROI where pH < 5.5
Bundled ISFM kit (seed + P + training)	10% - 15% kit discount	+12 - 20 pp for first-time adopters	+$40 - 70/ha; compounded by variety response

(pp = percentage points of farmers adopting).

Table 7 presents a summary of the simulated impacts of different fertilizer subsidy instruments on ISFM adoption and farm, level profitability. Findings indicate that price-based measures can significantly raise adoption levels, but the extent of their effectiveness depends on how well the subsidy is aligned with the soil constraints and farmer decision, making barriers. A blanket 30% fertilizer subsidy leads to a moderate increase in ISFM adoption (10, 18 percentage points), mainly by alleviating the liquidity constraints of smallholders at the time of planting. The resulting margin increases of USD 55, 85/ha come mainly from lower cash requirements rather than yield gains. This implies that while broad subsidies help make the product affordable, they may be less effective in guiding the use of nutrients to their most limiting functions.

On the other hand, a proposal for a phosphorus voucher, which is only valid for banded application, will provide higher returns per dollar of public expenditure especially in acidic soils where the availability of phosphorus is the main factor limiting the yields. Adoption increases are slightly less (8, 12 percentage points), but the margin improvement of USD 35, 60/ha is mainly in the areas where the greatest agronomic responsiveness (pH < 5.5) points to the effectiveness of spatially and technically targeted subsidies. The combined ISFM kit elicits the strongest adoption response (12, 20 percentage points), especially among first, time adopters. This simultaneously removes barriers to input access, knowledge gaps, and varietal performance. The aggregated margin effects (USD 40, 70/ha) include both cost savings and synergistic yield improvements, suggesting that integrated subsidy schemes are more effective than single, input support in facilitating sustained ISFM adoption.

7.4. Labor Constraints and Mitigation

Table 8. Labor Constraints and Mitigation

Constraint	Yield/cost impact	Practical mitigations
OM handling (compost/manure transport)	+$25 - 40/ha labor cost; adoption dips −6 - 10 pp	Promote on-farm pit composting, OM hubs near plots; two-wheel carts; focus on 2 t/ha minimum viable rate.
Water control (bunding/drains)	+$20 - 30/ha in year 1; yield +7% - 12% in uplands/IVS	Stagger works; cash-for-work support pre-season; communal bunds.
Precision placement (banded P, split N)	Adds 1 - 2 labor-days; improves NUE +5% - 10%	Row-markers, simple banders, extension demos; tie to P voucher.

Table 8 reveals labor availability to be a top non, price constraint that significantly influences both the adoption and performance of ISFM. Labor for the management of organic matter results in the biggest labor load and therefore the largest cost increase which is between USD 25, 40/ha and the decrease in adoption is between 6, 10 percentage points, thus, pointing to the significance of labor, saving strategies such as simple on, farm compost pits, organic matter hubs at the local level, and using a minimum viable application rate of 2 t/ha.

Water control measures like bunding and drainage may require extra labor input in the first season. However, they bring about significant yield increases (7, 12%) in both upland and inland valley swamp systems. As such, pre-season labor support through communal works or cash-for-work programs is well justified. Precision nutrient placement practices entail only a small increase in labor (1, 2 labor, days), yet they lead to a marked improvement in nutrient use efficiency (5, 10%). Thus, it is clear that simple tools, practical demonstrations and a connection to targeted input vouchers can efficiently pay for the labor while at the same time increasing the agronomic efficiency.

7.5. Combined Program Scenarios

- **Scenario A—"Acid-Soil Booster"**: pH-screening + banded P voucher + micro-dosed lime strips.

Outcome: mitigates pH penalty (~6% - 18% yield loss) to ≤5%, boosts adoption + 10 - 15 pp in acidic belts.

- **Scenario B—"Labor-Light ISFM"**: 2 t/ha OM minimum (near-field sources), 60 - 75 kg N/ha split, no-till mulch + communal bunds.

Outcome: preserves ~80% - 90% of ISFM yield gains with ~30% - 40% less labor than 4 t/ha OM; adoption +8 - 12 pp.

- **Scenario C—"Starter Kit for First-Time Adopters"**: improved seed + 60 kg N-equiv + banded P applicator + 1 training.

Outcome: rapid uptake (+15 - 20 pp), stable NUE, yields approach ISFM-standard in year 1; OM ramp-up in year 2.

8. Discussion

The findings of this research offer compelling empirical and theoretical evidence supporting the use of Integrated Soil Fertility Management (ISFM) as a strategy with a high impact on increasing rice productivity in different agro, ecological areas of Liberia. The yield responses indicate that the combination of organic matter inputs with moderate rates of mineral nitrogen leads to significantly higher productivity compared to either input alone, in line with the well, known ISFM principle that it not only provides nutrient availability for a short period but also improves soil quality in the long run [28] [29]. The Mitscherlich response curves indicate that the yields tend to level off earlier when organic matter is added, suggesting that organic inputs allow mineral nitrogen to be more efficiently converted into grain. This is consistent with the results of [30] and [31] who demonstrated that nutrient synergy in tropical soils lowers nutrient losses and enhances physiological nutrient uptake. This matter is very significant for Liberia's rice systems which frequently face nutrient depletion and hardly use external inputs.

Nutrient Use Efficiency (NUE) trends from the analysis also follow previous literature which reports diminishing marginal returns to nitrogen as application rates increase. Still, the incorporation of organic matter lessens this drop, keeping NUE at higher nitrogen levels which are a proof that organic inputs improve the synchrony of nutrient release with crop demand [32] [33]. Several nutrient use studies in West Africa have also demonstrated that small additions of OM (24 t/ha) greatly enhance the nitrogen recovery efficiency in severely degraded soils [34]. The increased NUE under ISFM conditions predicted by the model means that Liberia might be able to reduce the total nitrogen needed for smallholder rice production thus saving money and reducing the risk of environmental hazards such as nitrate leaching and ammonia volatilization.

The long, term improvement of soil health is thus a major factor. This is in line with the Soil Organic Carbon (SOC) trajectory which emphasizes long, term soil health benefits. Soil Organic Carbon dropped drastically in the absence of organic matter, a situation that has been repeated in West African Ferralsols and Acrisols that were continuously cultivated without the return of residues [35]. On the other hand, the use of organic matter over a long time ensured a slowdown in the loss of SOC and at the higher input level (4 t/ha) it was even able to reverse the long, term negative trends. Also, the Africa Soil Information Service (AfSIS) and long, term experiments in Cte d'Ivoire and Nigeria sources have shown that 3 to 5 t/ha of organic matter application is necessary yearly for the gradual restoration of carbon stocks in humid tropical regions.

Besides, better SOC results to improved soil aggregation, higher water retention capacity and greater biological activity of the soil which are the main factors that make crops more resistant to rainfall variability that is a major vulnerability of Liberia's upland and rain, fed lowland rice ecologies.

The sensitivity analysis further refines the picture by showing that rainfall variability and soil acidity remain the major factors affecting the yields, even when best ISFM treatment is used. A 20% change in rainfall resulted in 1022% variations in yield, which is in line with the literature pointing to water availability as being the key factor determining nutrient response in humid West African rice systems [36]. The decrease in yield due to acidic soils, particularly under pH 5.5, was quite significant as a result of phosphorus fixation and root damage, a problem which is widely known in Liberia and has been confirmed in Sierra Leone and Ghana through research [37].

Furthermore, high, quality organic matter helped increase yields and NUE, whereas low, quality OM reduced short, term productivity but enabled long, term SOC accumulation, a compromise that is recognized in the organic resource quality framework by [38].

In spite of the strength of the modeling framework, several limitations should be pointed out. Most of the results are based on secondary datasets and calibrated response functions rather than on extensive primary field trials carried out specifically in Liberia [39]. Thus, the modeled yield results are theoretical averages under certain assumptions and might not adequately reflect the heterogeneity of on, farm conditions, such as small variations in soil fertility, farmer management skills, pest pressures, and local climate shocks.

Besides, the farmers' fields are likely to have patchy nutrient distribution and varying input application, which might lead to yield responses lower or more variable than simulated estimates. In addition, the Mitscherlich model presupposes smooth and continuous yield responses that may not correspond to threshold effects or nonlinear constraints that exist under severe nutrient stress [40].

These limitations, however, do not invalidate the conclusions. They rather serve as a warning that the yield gains projected by the models should be viewed as a potential indication instead of a promise, which is why on, farm validation trials and adaptive extension approaches are vital to improving ISFM recommendations in real, world situations.

9. Policy Recommendations

1) Prioritize water & acidity first: finance bunding/mulch in uplands and banded P + micro-liming where $pH < 5.5$; these stabilize responses to N and OM.

2) Subsidize smart, not flat: replace blanket fertilizer subsidies with targeted P vouchers tied to band placement and acidity mapping; keep a modest N co-pay to maintain efficiency.

3) Lower the labor hump: promote on-farm compost pits, near-field OM, and simple placement tools; support cash-for-work for communal water works pre-season.

4) Package ISFM as kits: seed + (modest) N + banded P + one training; escalate OM rate over 2 - 3 seasons as SOC and logistics improve.

5) Extension metrics: track NUE, pH screening coverage, bund length constructed, and OM rate achieved (not just fertilizer tons).

6) County targeting: roll out "Acid-Soil Booster" where pH < 5.5; deploy "Labor-Light ISFM" in labor-scarce uplands; use "Starter Kits" for low-adoption districts.

Conflicts of Interest

The author declares no conflicts of interest.

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