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Computational Multivariate Framework for Assessing Agricultural Carbon Emissions across Crop, Soil and Fertilizer Management Factors

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ABSTRACT
Agricultural carbon emissions reflect the combined influence of crop characteristics, soil conditions and input-management decisions. This study integrates two complementary descriptive analyses: (i) the association between chemical versus organic fertilizer treatment and carbon emissions, and (ii) the three-way structure of crop type × soil type × fertilizer-loss level. The supplied dataset contains 45 crop–soil–loss combinations covering citrus, corn, rice, vegetable and wheat; clay, loamy and sandy soils; and low, medium and high fertilizer-loss levels. Total CO_2e is the principal outcome. The results show a highly consistent monotonic increase in Total CO_2e from low to medium to high fertilizer loss across every crop–soil combination. Mean Total CO_2e is approximately 232.63 at low loss, 282.25 at medium loss and 331.97 at high loss, giving an average low-to-high difference of about 99.34 CO_2e units. Rice has the highest crop-wise average, while vegetables have the lowest. Mean differences among clay, loamy and sandy soils are comparatively small, and soil rankings vary across combinations. The fertilizer-treatment analysis additionally reports lower emission values under organic fertilizer than chemical fertilizer across the crops examined; the difference is largest in absolute terms for the higher-emission crops, particularly rice and corn. These findings identify fertilizer-loss management, nutrient-use efficiency and context-sensitive fertilizer selection as important dimensions of low-carbon agricultural management. The study is descriptive and associative; it does not establish causality or statistical significance. Future research should apply factorial models, uncertainty analysis and field-validated life-cycle emission measurements.
Keywords: Agricultural carbon emissions; CO_2e; fertilizer loss; nutrient-use efficiency; crop type; soil type; organic fertilizer; chemical fertilizer; sustainable agriculture; climate-smart agriculture

INTRODUCTION

Agricultural production is an important component of the climate–food system because crop production depends on energy, fertilizers, water and other inputs whose production and use can generate greenhouse-gas emissions. Agriculture is also closely connected to the nitrogen cycle, through which losses of applied nutrients can contribute to atmospheric emissions and water pollution [11, 26, 29, 33]. The mitigation literature therefore increasingly treats fertilizer management as part of a wider agricultural-system problem rather than as an isolated input issue [3, 12, 25].

Nitrogen fertilizer is particularly important because emissions can arise during manufacture and after application to soils. Field emissions are affected by soil conditions, moisture, nitrogen availability, crop demand and management practices [2, 28, 29]. At the same time, fertilizer losses represent inefficient use of resources: nutrients that leave the crop–soil system without supporting production may create pressure for additional inputs and increase the environmental burden associated with those inputs [5, 8, 17].

The present study extends the analysis by bringing fertilizer treatment and fertilizer loss into a common framework. It asks three questions: (1) Is chemical fertilizer consistently associated with higher carbon-emission values than organic fertilizer in the supplied analysis? (2) Does increasing fertilizer loss correspond to a systematic change in Total CO_2e across crops and soils? and (3) Whether the variability in fertilizer loss is greater than the variability attributable to soil type. The purpose of this study is descriptive rather than causative: This research will identify relationships between variables that may guide future statistical or field research.

Additionally, this study relates to both sustainable intensification and climate-smart agriculture. Sustainable intensification aims to increase food production while decreasing negative impacts on the environment [12, 24, 31]. Climate smart agriculture includes various combinations of agricultural practices that enhance food security, promote adaptability to climate change, and mitigate greenhouse gases [18, 3]. Both approaches encourage assessment of fertilizer source, application rate, timing, location, and loss collectively rather than individually.

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2. LITERATURE REVIEW

2.1 Fertilizer management and greenhouse-gas emissions

Fertilizer management is one of the primary methods used to mitigate greenhouse gases from agriculture. Studies have shown that fertilizer type, application rate, timing, and placement affect greenhouse gas emissions, and that nitrogen management interacts with crop and soil characteristics [22, 27, 28, 32]. Production and use of synthetic nitrogen fertilizer can account for a significant portion of the total agricultural carbon footprint; global assessments attribute emissions to manufacturing, transporting, and applying fertilizer [23, 35]. These studies provide a larger context for comparing CF-OF in the current dataset. Because fertilizer-related emissions originate at many stages throughout the product lifecycle, the life-cycle perspective is essential. Emission factors vary based upon production pathway, fertilizer type, storage method, application method, soil type, crop type, and management techniques [36, 38]. Therefore, a lower measured emission value for one fertilizer treatment in a given dataset should not be taken as a general ranking of all products under all system boundaries.

2.2 Nutrient-use efficiency and fertilizer loss

Nutrient-use efficiency refers to how well applied nutrients are utilized in producing crops versus lost from the production system. The 4R nutrient stewardship framework (right source, right rate, right time, right place) provides a usable framework for enhancing nutrient-use efficiency [15, 16, 9]. Previous studies have stressed the need to match nutrient availability to crop requirements [5, 8], and global assessments continue to indicate opportunities exist to enhance nitrogen-use efficiency [17]. There are several ways that fertilizer can be lost from the production system including volatilization, leaching and gaseous transformation. Extreme weather events can cause increased nutrient loss [14] while soil and environmental conditions affect microbial processes involved in N_2O emissions [2]. Meta-analysis results demonstrate that enhanced-efficiency fertilizers and improved management can reduce some nutrient losses and greenhouse gas emissions; however, outcomes depend on context [6, 37]. Thus, the present study considers fertilizer loss as representative of a larger input-efficiency issue rather than as a single measured biochemical pathway.

2.3 Fertilizer source: chemical versus organic

Chemical and organic fertilizers may differ in their production pathways, nutrient content, mineralization dynamics and field emissions. Life-cycle studies caution that emission factors vary considerably across fertilizer products and production systems [36, 38]. Likewise, reviews of organic and mineral fertilization show that both types of fertilizers can alter CO_2, CH_4 and N_2O emissions and that outcomes depend on management and soil conditions [13].

Consequently, the present finding that chemical fertilizer results in greater emission values than organic fertilizer should be viewed as a dataset specific association. This observation is consistent with literature demonstrating substantial emissions from synthetic nitrogen supply chains [23, 39], but it does not independently establish whether the differences observed here result from fertilizer manufacturing, transportation, application, soil processes or other elements.

2.4 Crop, soil and system effects

Crop type can alter emission patterns since nutrient demand, water availability, biomass accumulation and management intensity vary among crops. Rice, for instance, exhibits unique greenhouse gas dynamics resulting from saturated soil conditions and nitrogen management [18]. Global assessments also indicate considerable variation in greenhouse gas emission intensity among cropland types [4]. Soil characteristics can modify nutrient retention, moisture and microbial processes [2] while nutrient balance indicators stress the importance of avoiding excessive surpluses [10]. The literature increasingly supports integrative management rather than isolated interventions. Site-specific nutrient management can enhance input efficiency and decrease greenhouse gas emissions while maintaining productivity [7, 34]. Similarly, meta-analyses of management practices show that the environmental impact of a practice depends on crop type, soil type and management context [20, 24, 37].

2.5 Research gap

Much previous research examines fertilizer management, crop systems, soil processes or life-cycle emissions separately. The supplied dataset provides a compact analytical structure in which crop type, soil type, fertilizer treatment and fertilizer-loss level can be considered together. The contribution of the present study is therefore the systematic description of the direction and magnitude of these patterns across a common set of crop–soil combinations, not causal identification.

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3. MATERIALS AND METHODS

3.1 Data and variables

The study uses the dataset supplied with the analysis document. The principal three-factor dataset contains 45 observations generated by 5 crops × 3 soil types × 3 fertilizer-loss levels. Crop categories are citrus, corn, rice, vegetable and wheat. Soil categories are clay, loamy and sandy. Fertilizer-loss levels are low, medium and high. Total CO_2e is the outcome variable. A complementary fertilizer-treatment analysis compares chemical fertilizer (CF) and organic fertilizer (OF) across the crop categories.

The analytical unit is therefore a crop–soil–loss combination. The study does not claim a randomized experiment, causal intervention or inferential statistical test. All conclusions are expressed as descriptive patterns, differences or associations. This distinction is important because observed emission differences may also reflect unmeasured fertilizer rates, yields, water management, weather, soil chemistry, life-cycle boundaries and other factors [2, 36].

3.2 Analytical approach

The analysis compares Total CO_2e across crop, soil and fertilizer loss categories. Descriptive questions about four aspects will be addressed in detail. These are: (i) Does the loss gradient show a monotonic relationship? (ii) What is the magnitude of change in Total CO_2e from low to high loss levels? (iii) How much variation exists among different soil types at each loss level? (iv) Which direction does the CF–OF comparison take? The means of crop-wise and soil-wise values are calculated using 45 observations. Low to high differences have been selected to provide an example of sensitivity. The conceptual framework for the analysis is: Crop Type × Soil Type × Fertilizer Treatment × Fertilizer Loss → Total CO_2e. Within this framework, crop type provides a broad baseline for variation, fertilizer treatment modifies the emissions level, soil type introduces minor contextual variations, and fertilizer-loss level presents the greatest consistency in the provided data. This conceptual framework is purely descriptive and should not be viewed as a fitted statistical interaction model.

4. RESULTS

4.1 Overall crop and soil patterns

Crop	Mean Total CO_2e
Citrus	260.48
Corn	294.44
Rice	348.30
Vegetable	233.87
Wheat	274.33

Table 1. Crop-wise mean Total CO_2e across the 45-observation dataset.

Soil	Mean Total CO_2e
Clay	281.93
Loamy	281.91
Sandy	283.01

Table 2. Soil-wise mean Total CO_2e across the 45-observation dataset.

Rice has the highest crop-wise mean Total CO_2e, while vegetables have the lowest. The soil means are close to one another: approximately 281.93 for clay, 281.91 for loamy and 283.01 for sandy soil. Thus, crop type contributes much more to the broad baseline separation than soil category in this dataset. However, soil is not irrelevant; the relative ranking changes across specific crop–loss combinations.

4.2 Fertilizer-loss gradient

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Loss level	Mean Total CO_2e	Difference from Low
Low	232.63	—
Medium	282.25	49.62
High	331.97	99.34

Table 3. Mean Total CO_2e by fertilizer-loss level.

The strongest descriptive pattern is the monotonic increase Low < Medium < High. Mean Total CO_2e rises from approximately 232.63 at low loss to 282.25 at medium loss and 331.97 at high loss. The average low-to-high difference is therefore about 99.34 CO_2e units. The same direction is observed in every crop and every soil category.

For citrus in clay soil, Total CO_2e increases from 209.62 at low loss to 260.84 at medium loss and 310.66 at high loss. For rice in sandy soil, the corresponding values are 297.92, 349.37 and 400.44. The repetition of the same directional pattern across five crops and three soils is the central empirical feature of the supplied analysis.

4.3 Sensitivity to fertilizer loss

Crop–soil combination	Low	High	Increase
Citrus–Clay	209.62	310.66	+101.05
Corn–Clay	245.05	343.25	+98.19
Rice–Sandy	297.92	400.44	+102.52
Vegetable–Loamy	182.92	284.92	+102.00
Wheat–Sandy	225.38	324.91	+99.53

Table 4. Representative low-to-high fertilizer-loss changes.

The low-to-high increase is remarkably stable, ranging from approximately 98.19 to 102.52 CO_2e units in the representative combinations. This suggests high descriptive sensitivity of Total CO_2e to fertilizer-loss level. The finding is consistent with the broader literature linking nutrient losses and nitrogen management to greenhouse-gas outcomes [1, 2, 21, 28]. Nevertheless, the dataset does not directly measure the biochemical or life-cycle mechanism responsible for the increase.

4.4 Fertilizer treatment: chemical versus organic

The added fertilizer-treatment analysis reports a consistent CF > OF pattern across all five crops. Chemical fertilizer is associated with higher emission values than organic fertilizer in every crop category examined. The supplied text gives explicit examples: rice records approximately 353.05 under chemical fertilizer versus 345.43 under organic fertilizer; wheat records 276.75 versus 270.10; and vegetables record 238.17 versus 229.72. The supplied figures additionally show the same direction for citrus and corn.

Crop	Chemical fertilizer (CF)	Organic fertilizer (OF)	Observed direction
Rice	353.05	345.43	CF > OF
Wheat	276.75	270.10	CF > OF
Vegetable	238.17	229.72	CF > OF
Corn	Higher	Lower	CF > OF
Citrus	Higher	Lower	CF > OF

Table 5. Fertilizer-treatment comparison reported in the supplied analysis.

The consistency of the direction is notable because the crop changes while the fertilizer-treatment relationship does not reverse. The analysis therefore supports treating fertilizer source as a separate dimension of agricultural carbon-footprint assessment. However, it does not establish that organic fertilizer is universally lower-carbon: fertilizer source, processing, transport, nutrient content, application rate and system boundaries can materially change life-cycle outcomes [13, 36, 38].

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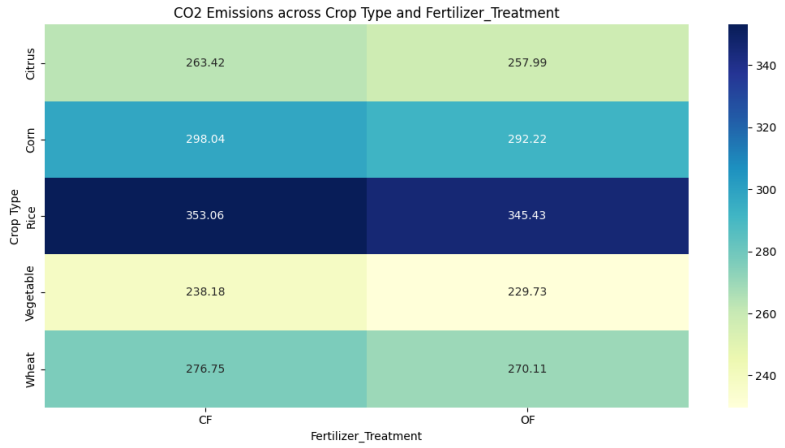


Figure 1. CO_2 emissions across crop type and fertilizer treatment as supplied in the analysis document.

4.5 Crop-wise magnitude of the fertilizer-treatment difference

The supplied analysis indicates that the absolute reduction associated with the CF-to-OF change is more pronounced in higher-emission crops, particularly rice and corn, and smaller in lower-emission crops such as vegetables. This is an absolute-difference interpretation: a high-emission crop has more numerical scope for reduction even when the percentage difference may be similar to another crop. The analysis therefore recommends distinguishing absolute and percentage reductions before ranking crops for mitigation.

Rice is especially important because it combines the highest crop-wise emission level with the largest reported fertilizer-treatment reduction. Corn also shows a relatively large reduction. Vegetables show the smallest absolute reduction, but this does not imply that organic fertilizer is unimportant; their lower baseline means that a smaller absolute change can still represent a meaningful environmental advantage. Crop-specific nutrient requirements and productivity must remain part of any management decision [4, 18, 31].

4.6 Crop × soil × fertilizer-loss interaction pattern

The three-factor results show that fertilizer loss does not merely change emissions in one crop or one soil. Citrus, corn, rice, vegetable and wheat all follow Low < Medium < High, and the same direction occurs in clay, loamy and sandy soils. Crop type changes the baseline level, soil type introduces comparatively small variation, and fertilizer-loss level produces the most consistent change. This can be summarized as: crop type → baseline emission profile; soil type → contextual modification; fertilizer treatment → emission-level shift; fertilizer loss → strong and systematic gradient.

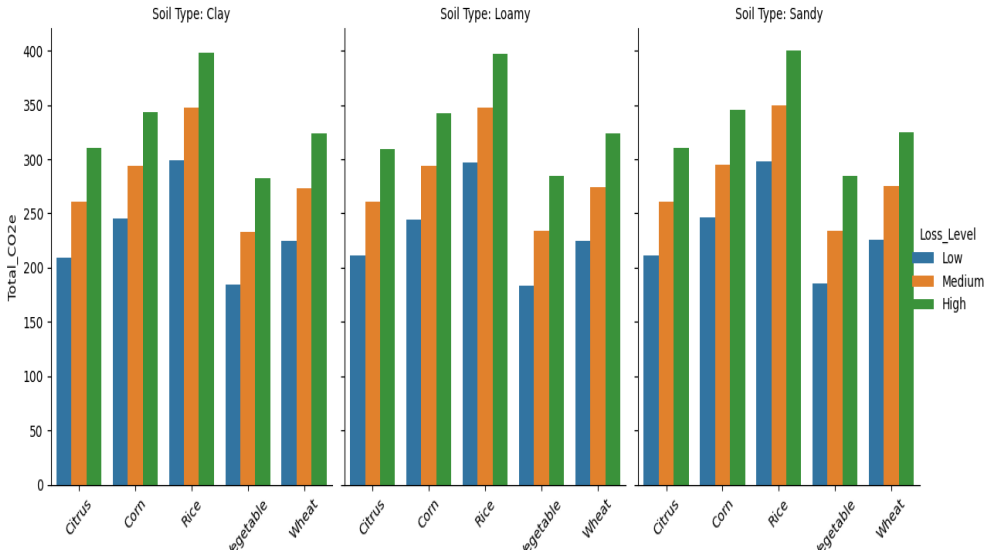


Figure 2. Total CO_2e by crop, soil type and fertilizer-loss level in the supplied analysis.

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4.7 Soil influence and its interpretation

Soil type contributes relatively small variation compared with fertilizer loss. For citrus, for example, low-loss values are approximately 209.62 for clay, 211.20 for loamy and 211.25 for sandy soil. At high loss, the values are approximately 310.66, 308.91 and 309.98, respectively. The range among soils is therefore much smaller than the roughly 100-unit low-to-high change associated with fertilizer loss.

It is important not to overstate the role of sandy soil. The full dataset does not show sandy soil as consistently highest. In some combinations sandy is highest, whereas in others clay or loamy soil is higher. A scientifically appropriate conclusion is that soil type introduces small but observable variation whose direction differs by crop and loss level. This interpretation is consistent with literature emphasizing that soil properties modify nutrient retention, water movement and microbial processes [2, 14, 20].

4.8 Statistical Extensions Recommended for Future Validation

n addition to incorporating uncertainty analysis into future work, the variability of fertilizer emission factors due to differences in production pathway, energy source, storage, transport, application methods, soil characteristics, and system boundary definitions [13, 36], means that the reliability of a carbon-footprint model would be improved if it were able to provide estimates of the range of uncertainty associated with each of the emission factor components. The three-factor data set also lends itself to conducting structured sensitivity analyses. For each crop-soil pair, the percent increase or decrease (relative to a base case) can be estimated; the mean and standard deviations of these percentages can be reported. The roughly 100-unit pattern observed in the example provided can then be formally evaluated using quantitative measures instead of qualitative descriptions. As long as the underlying data used to create the model's predictions are clearly identified as being generated by the model itself, rather than being derived from independent measurements, then the distinction will have important implications when interpreting statistical inferences.For example, if the model-generated data are used to derive an estimate of the "treatment" effect for the fertilizer treatment analysis, then the two-factor model consisting of crop and fertilizer treatment can be used to determine if there is a statistically significant difference between the CF-OF values, and if so, how much of that difference is explained by variations among crops. An interaction term would be very useful in this case since the descriptive analysis indicated that although the direction of the effect may remain constant, its magnitude may differ depending upon the crop. Effect sizes and confidence intervals should accompany p-values to prevent researchers from mistaking statistical significance for practical significance.While the present study is primarily descriptive, the consistency of the patterns observed provides a sound basis for formally validating the statistical models that were developed. However, the present analysis should not be viewed as an experimental design. A logical follow-up would be a factorial analysis with crop type, soil type, and loss-from-fertilizer as categorical variables and Total CO_2e as the dependent variable. In addition to estimating main effects and interaction terms, the model could determine if the apparent loss-from-fertilizer gradient continues to show statistical significance after considering crop and soil.

4.9 Practical Management Scenarios Derived from the Analysis

The most immediate action that can be taken on behalf of farmers and their extension programs will likely come from the consistent low < medium < high pattern of fertilizer loss across all crops and soil types. The potential actions that could be taken by farmers and extension programs include improved timing and placement of fertilizers; improved selection of fertilizer rates; development of soil-specific fertilizer recommendations; and monitoring. It is important to evaluate these actions based upon their ability to reduce CO2e; increase yield; improve farm income; maintain soil health; protect water quality; and maintain long term nutrient balance. Lower emission crops (e.g. vegetables) are still subject to low fertilizer loss regardless of whether or not the difference in fertilizer treatment is large. In other words, a low baseline emission does not provide justification for inefficient nutrient utilization. The sustainability objective is to ensure that the system does not shift from a low emission baseline to a higher emission baseline due to excessive or poorly timed applications of fertilizer. For higher emission crops (e.g., rice), the data indicates two primary objectives for management: increase fertilizer efficiency and evaluate lower emission fertilizer alternatives that are agronomically acceptable. In the provided analysis, rice grown with chemical fertilizers represents a high emission crop-fertilizer combination.

However, rice growers must protect both productivity and nutrient demand. Therefore, the management objective should be optimal delivery of nutrients rather than a blanket replacement policy. Four general management strategies are identified in relation to the results. Scenario #1 represents a low loss system in which nutrient delivery is closely tied to the needs of the crop. The dataset suggests that this scenario has the lowest CO2e values for each crop-soil combination. Scenario #2 represents a mid-level loss system, with emissions rising to a mid-range level. Scenario #3 represents a high-loss system, with CO2e significantly higher. Scenario #4 combines fertilizer-source selection with loss reduction, illustrating the broader conclusion drawn in this study that both fertilizer treatment and nutrient utilization efficiency need to be managed simultaneously.

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4.10 Nutrient-Use Efficiency as the Link Between Fertilizer Loss and Carbon Footprint

The integrated study therefore supports a policy direction in which carbon accounting is connected to nutrient accounting. A carbon-footprint assessment that records only fertilizer quantity may overlook whether the applied nutrient was efficiently used. Adding loss and nutrient-use-efficiency indicators can make the assessment more informative and potentially more actionable for farmers, extension services and policymakers.

Potential interventions include soil testing, crop-specific nutrient recommendations, split applications, improved placement, fertigation where appropriate, controlled-release fertilizers, nitrification or urease inhibitors, and monitoring of nutrient losses. Such interventions are not automatically effective in every setting; their performance depends on soil, climate, crop and management conditions. Recent reviews likewise emphasize site-specific nutrient management and the importance of evaluating trade-offs between fertilizer efficiency, productivity and greenhouse-gas mitigation [31, 36].

The management implication is not that fertilizer use should be minimized without regard to crop requirements. Nutrients are essential for productivity, and inadequate fertilization can reduce yields and degrade farm profitability. The more appropriate objective is to provide the right nutrient, in the right amount, at the right time and by an appropriate method. This principle is consistent with the 4R nutrient-stewardship framework and with research on enhanced-efficiency fertilizers and controlled-release systems [8, 14, 31].

Nutrient-use efficiency provides a useful bridge between the descriptive fertilizer-loss findings and agricultural sustainability. Efficient nutrient management means that a greater proportion of applied nutrients contributes to crop growth rather than being lost through volatilization, leaching, runoff or other pathways. The literature emphasizes that high nutrient losses reduce fertilizer-use efficiency and can increase environmental burdens, including greenhouse-gas emissions [14, 20, 31, 36]. The present dataset adds a descriptive carbon-footprint perspective by showing that higher fertilizer-loss categories are consistently associated with higher Total CO_2e

4.11 Integrated Interpretation of Crop, Soil, Fertilizer Treatment and Fertilizer Loss

The integrated framework has relevance for decision-support systems. A future computational model could use crop type, soil type, fertilizer source, fertilizer application rate and fertilizer-loss indicators as predictors of estimated carbon footprint. Such a model could then identify combinations with comparatively high emissions and simulate management alternatives. Machine-learning methods could be considered for prediction if a sufficiently large and independently validated dataset becomes available, while regression or factorial ANOVA would be appropriate starting points for inferential assessment of the present structured dataset.

The data also show that the relative importance of factors is not identical. Fertilizer loss produces the most pronounced and stable change in the observed CO_2e values. Crop type determines large differences in baseline emission levels, with rice among the higher-emission crops and vegetables among the lower-emission crops in the supplied analysis. Soil differences are comparatively small and do not follow a single universal ranking. This hierarchy is descriptive rather than statistical; formal effect sizes and significance tests would be needed before assigning quantitative causal importance to the factors.

The important contribution of the integrated analysis is that it avoids treating fertilizer management as a single binary decision. A farmer can choose a fertilizer source but still experience substantial nutrient losses. Conversely, a farmer can reduce losses while using a fertilizer whose production or application has a relatively high carbon intensity. Therefore, source selection and loss management should be considered jointly. The strongest sustainability strategy is not simply ‘organic instead of chemical’, but efficient nutrient supply that matches crop demand, soil conditions and application timing while minimizing avoidable losses.

The combined evidence from the two supplied analyses supports an integrated conceptual framework for agricultural carbon emissions. Crop type influences the baseline level of emissions; soil type introduces contextual variation; fertilizer treatment is associated with a consistent shift between chemical and organic fertilizer conditions; and fertilizer loss is associated with a strong Low–Medium–High emission gradient. The framework can therefore be represented as: Crop type + Soil type + Fertilizer treatment + Fertilizer loss → observed agricultural CO_2e.

4.12 Soil Effects: Context Rather Than a Uniform Ranking

The interaction perspective is consequently more informative than a single soil ranking. Crop type establishes a broad emission profile, soil type modifies the conditions under which nutrients are retained and transformed, and fertilizer loss produces the most systematic shift in observed CO_2e. This three-factor interpretation provides a stronger basis for future inferential modelling, in which crop, soil and loss level could be represented simultaneously rather than analysed separately.

This finding is consistent with the broader understanding that soil properties can influence nutrient retention, water movement, microbial activity and fertilizer-use efficiency. Soil should therefore not be ignored, even though it is not the dominant descriptive gradient in this dataset. Instead, soil can be treated as a contextual or moderating

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factor within a wider nutrient-management system. Site-specific nutrient management is especially relevant because fertilizer efficiency depends on environmental and soil conditions [14, 20, 31].

The full dataset also demonstrates why it would be inappropriate to conclude that sandy soil always has the highest emissions. Sandy soil is highest in some crop–loss combinations, but clay or loamy soil is higher in others. For example, under high fertilizer loss in vegetables, loamy soil records about 284.92 CO_2e, compared with 282.14 for clay and 284.26 for sandy soil. The appropriate interpretation is therefore that soil type introduces small but observable variation, and that the direction of this variation depends on the crop and fertilizer-loss condition.

The soil results require a more nuanced interpretation than a simple ranking of clay, loamy and sandy soils. In the supplied data, soil type changes the emission level only modestly relative to the fertilizer-loss gradient. For citrus at low loss, the values are 209.62 for clay, 211.20 for loamy and 211.25 for sandy soil. The difference between the lowest and highest values is approximately 1.63 CO_2 units. At high loss, citrus records approximately 310.66 for clay, 308.91 for loamy and 309.98 for sandy soil. Again, the soil differences are small relative to the approximately 100-unit change associated with low-to-high fertilizer loss.

4.13 Fertilizer Loss as an Emission-Sensitivity Gradient

The nutrient-use-efficiency interpretation provides a plausible conceptual pathway. When a larger share of applied nutrients is lost rather than utilized by the crop, the resources embodied in fertilizer production and application are not fully converted into agricultural output. Additional fertilizer may then be required to maintain nutrient availability. This creates a potential chain from higher loss to lower nutrient-use efficiency, greater input wastage, additional fertilizer requirement and a larger associated carbon footprint. The present dataset does not directly measure each of these intermediate mechanisms, so the pathway should be treated as an interpretation supported by the literature rather than as a demonstrated causal mechanism.

The term emission sensitivity is used here descriptively to denote the change in observed CO_2e across fertilizer-loss categories. It does not imply that the dataset estimates a causal response function. Nevertheless, the approximately 100-unit change between low and high loss is substantially larger than many of the differences observed among soil types at a common loss level. This contrast is useful because it identifies fertilizer-loss management as a potentially important dimension for further statistical testing and intervention design.

The magnitude of the low-to-high change is also relatively stable. Citrus under clay soil increases from 209.62 CO_2e at low loss to 310.66 CO_2e at high loss, a difference of approximately 101.05 units. Corn under clay increases by about 98.19 units, rice under sandy soil by about 102.52 units, vegetables under loamy soil by about 102.00 units, and wheat under sandy soil by about 99.53 units. The consistency of these differences suggests that fertilizer-loss level is closely associated with the level of CO_2e represented in the dataset.

The most pronounced descriptive pattern in the three-factor dataset is the progressive increase in Total CO_2e from Low to Medium to High fertilizer loss. This sequence occurs for all five crops and all three soil types. It can therefore be represented as Low fertilizer loss < Medium fertilizer loss < High fertilizer loss. Unlike a relationship that appears only in a single crop or soil, this gradient is repeated throughout the 45 crop–soil–loss combinations and is one of the strongest structural features of the dataset.

4.14 Crop–Fertilizer Combinations and Carbon-Reduction Priorities

The reduced absolute emissions for vegetables may not be seen by many people as having a significant impact on our environment; however, we know from studies that even a relatively "clean" crop will benefit from reduced loss and emissions through proper nutrient management. One area of concern is how we define an absolute vs. relative reduction. If possible, a subsequent study should calculate the percent reduction for each crop using $[(CF - OF)/CF] \times 100$ and if available, should also assess emissions per unit of crop produced. Both assessments would provide additional information to help farmers develop better decisions regarding their agricultural practices. Mitigation strategies related to rice are of particular interest due to its high ranking among all other crops in terms of overall emissions and also due to its significantly larger absolute difference in emissions between using chemical vs. organic fertilizers.Another candidate for targeted fertilizer management interventions is corn. While this analysis does not suggest that chemical fertilizers should be eliminated, it does suggest that we need to find ways to improve nutrient use efficiency and reduce emissions per unit of agricultural production, as opposed to simply substituting one form of fertilizer for another. The combination of organic fertilizer and lower-emission vegetables represents the combination of two factors that were identified in the analysis separately. Vegetables have a relatively low baseline emission level and organic fertilizer has been shown to produce less emissions than chemical fertilizer.On the other hand, the combination of chemical fertilizer and higher-emission rice represents a combination of higher emission fertilizer with higher emission rice. Therefore, this finding emphasizes the fact that we need to view agricultural practices as interrelated management systems, rather than isolated variables. This analysis provides a method for translating the descriptive results into management priorities. Vegetable cultivation with organic fertilizer recorded the lowest reported crop-fertilizer emission value at approximately 229.72 CO_2. Rice cultivated with chemical fertilizer recorded the highest reported crop-fertilizer emission value

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at approximately 353.05 CO_2. The difference in CO_2 values between these two combinations was 123.33 CO_2. These values demonstrate that the amount of carbon-emission levels may vary greatly depending upon the type of crop grown and the type of fertilizer used**.**

4.15 Detailed Crop-Wise Interpretation of Fertilizer Treatment

The observed CF > OF pattern should not be interpreted as evidence that every organic fertilizer is automatically more sustainable than every chemical fertilizer. Fertilizer source, production method, nutrient concentration, transport, storage, processing, application rate and field conditions influence life-cycle emissions. Published reviews also show considerable variability in emission factors for both synthetic and organic fertilizers and recommend case-specific assessment where possible [13, 36, 38]. The present study therefore supports the more limited conclusion that, under the conditions represented by the dataset, OF is associated with lower CO_2e values than CF.The crop-wise pattern also illustrates why mitigation priorities should consider both the baseline emission level and the size of the fertilizer-treatment difference. A high-emission crop may offer greater absolute mitigation potential even if its percentage reduction is not necessarily the largest. Conversely, a crop with a low baseline may show a smaller absolute change while still benefiting from a lower-emission fertilizer management strategy. This distinction is important for policy design because absolute reductions are useful for estimating aggregate mitigation potential, whereas percentage reductions are useful for comparing relative efficiency across systems.

Rice provides the clearest high-emission case. Its reported value is approximately 353.05 CO_2 under chemical fertilizer compared with 345.43 CO_2 under organic fertilizer. The absolute difference is about 7.62 units. Wheat shows a difference of approximately 6.65 units (276.75 versus 270.10), while vegetables show a difference of about 8.45 units (238.17 versus 229.72). The analysis document indicates the same direction for corn and citrus. These comparisons should be interpreted as differences within the supplied dataset rather than universal emission factors for the crops.The fertilizer-treatment analysis becomes more informative when the direction of the CF–OF difference is considered together with the baseline emission profile of each crop. The supplied analysis reports that chemical fertilizer (CF) is associated with higher carbon-emission values than organic fertilizer (OF) for every crop examined. The important feature is therefore not simply the existence of a difference, but the stability of its direction across crop categories. Rice, corn, wheat, citrus and vegetables all retain the same CF > OF relationship. This consistency indicates that fertilizer treatment contributes a systematic dimension to the observed variation in agricultural carbon emissions.

4.16 Complete Crop × Soil × Fertilizer-Loss Data Used in the Analysis

Crop	**Soil**	**Loss**	**Total CO_2e**
Citrus	Clay	Low	209.615628
Citrus	Clay	Medium	260.841913
Citrus	Clay	High	310.662040
Citrus	Loamy	Low	211.204050
Citrus	Loamy	Medium	260.984921
Citrus	Loamy	High	308.905449
Citrus	Sandy	Low	211.247633
Citrus	Sandy	Medium	260.907970
Citrus	Sandy	High	309.978753
Corn	Clay	Low	245.051023
Corn	Clay	Medium	293.701639
Corn	Clay	High	343.245799
Corn	Loamy	Low	244.290832
Corn	Loamy	Medium	294.373380
Corn	Loamy	High	342.687751
Corn	Sandy	Low	246.675554
Corn	Sandy	Medium	294.584234
Corn	Sandy	High	345.309541
Rice	Clay	Low	299.073784
Rice	Clay	Medium	348.024760
Rice	Clay	High	397.978784
Rice	Loamy	Low	297.126874
Rice	Loamy	Medium	347.825555

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Rice	Loamy	High	396.923797
Rice	Sandy	Low	297.921761
Rice	Sandy	Medium	349.373975
Rice	Sandy	High	400.438955
Vegetable	Clay	Low	184.762184
Vegetable	Clay	Medium	232.645251
Vegetable	Clay	High	282.136122
Vegetable	Loamy	Low	182.915420
Vegetable	Loamy	Medium	234.195046
Vegetable	Loamy	High	284.917834
Vegetable	Sandy	Low	185.295909
Vegetable	Sandy	Medium	233.711410
Vegetable	Sandy	High	284.259596
Wheat	Clay	Low	224.354403
Wheat	Clay	Medium	273.420815
Wheat	Clay	High	323.398778
Wheat	Loamy	Low	224.542806
Wheat	Loamy	Medium	273.986093
Wheat	Loamy	High	323.823218
Wheat	Sandy	Low	225.384070
Wheat	Sandy	Medium	275.173332
Wheat	Sandy	High	324.912257

Table 6. Complete 45-observation crop–soil–fertilizer-loss dataset reported in the supplied analysis.

The complete table verifies that the order of "low" < "medium" < "high" exists for all of the crop-soil combinations. However, the absolute levels vary significantly between the different types of crops; for example, rice has a large range, whereas vegetable crops have a smaller range. Citrus, corn, and wheat crops fall into an intermediate range. Regardless of which type of crop we consider, the three loss categories maintain the same relationship to one another across each of the three soil types. The purpose of including the table was to increase transparency and replicability. The reader can view the exact data that were used to generate the descriptive conclusions and use them as a foundation for additional statistical modeling. Since the analysis was conducted using the provided dataset, this table should not be viewed as a field study or as a national estimate of agricultural emissions.

4.17 Overall Analytical Synthesis

Taken together, the fertilizer-treatment analysis and the fertilizer-loss analysis provide complementary evidence. The CF-OF comparison addresses the source or treatment dimension of fertilizer management, whereas the Low-Medium-High loss comparison addresses how well applied nutrients are retained and utilized. The first comparison showed a consistent directional difference between fertilizer treatments; however, the second comparison showed a much larger and more systematic gradient associated with fertilizer-loss levels.

Therefore, these two findings should be read together rather than as competing explanations. The main analytical message is that carbon-efficient agriculture requires attention to both what is applied and what is lost. Fertilizer source affects the emission profile under the conditions represented by the dataset, while fertilizer loss appears to be associated with a substantially larger change in Total CO_2e. Soil remains important because it can alter nutrient retention and environmental conditions, but the present data do not support a universal soil ranking. Crop type remains vital because different crops operate at different baseline emission levels. This integrated interpretation provides a logical basis for the subsequent discussion of sustainability and policy. It also identifies a clear empirical agenda: validate the observed patterns using inferential statistics, include yield and economic variables, document the source of the emission factors, and test whether the same relationships persist under independently collected field data.

4.18 Implications for Carbon-Footprint Assessment and Decision Support

The findings suggest that agricultural carbon-footprint assessment should move beyond a single average emission value. The same fertilizer input can produce different observed emission levels depending on the crop, soil context, fertilizer treatment and degree of nutrient loss. A model that ignores these dimensions may therefore hide important differences between farming systems. The present analysis provides a compact structure for

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representing these dimensions jointly and can serve as a preliminary framework for a more comprehensive decision-support system.

A practical decision-support system could begin with crop and soil identification, followed by information on fertilizer source, application rate, timing and estimated loss. The system could then calculate or predict an associated CO_2e value and identify the factor combinations associated with comparatively high emissions. Such a tool would be especially useful when combined with field measurements because farmers could compare alternative nutrient-management scenarios before making an input decision.

The present results also suggest that carbon assessment should distinguish between emission level and emission reduction potential. Rice, for example, has a high baseline emission profile in the supplied data, so even a moderate percentage improvement could translate into a substantial absolute reduction. Vegetable systems have lower baseline values, meaning that absolute reductions may be smaller even when efficient management remains environmentally desirable. A decision-support system should therefore report baseline CO_2e, absolute reduction, percentage reduction and, where available, emissions per unit of yield.

Another important consideration is uncertainty. Fertilizer-related emission factors can vary according to production technology, energy source, storage, transport, soil properties and application conditions [13, 36]. Consequently, future versions of the framework should provide an uncertainty interval around predicted emissions rather than presenting a single value as exact. Sensitivity analysis can identify which input variables contribute most to uncertainty and therefore where additional field measurements would have the greatest value.

The framework can also support extension services and policy targeting. If high-loss conditions repeatedly correspond to higher CO_2e, extension programmes can prioritize nutrient-loss reduction practices. If certain crop–fertilizer combinations consistently show higher values, crop-specific guidance can be developed. Importantly, these recommendations should be evaluated jointly against productivity, farm profitability, soil health and water-quality objectives. Low carbon emissions alone do not define sustainable agriculture; rather, carbon efficiency should be integrated with agronomic and economic performance.

4.19 Proposed Integrated Low-Carbon Fertilizer Management Framework

Integrated Low-Carbon Fertilizer Management Framework (ILCFMF) can be broken down into five stages. The first stage of this framework is the diagnostic phase where you determine what kind of crop you're growing, the type of soil you're working with, the amount of nutrients your crop needs and how much fertilizer you're currently applying. The second stage of the framework is optimization of input: choosing the right type of nutrient and the amount needed based upon your crops' needs and the soil conditions. The third stage of the framework is optimization of application efficiency: improving when, where and how you apply fertilizer to ensure that the nutrients are available when and where your crops need them. The fourth stage of the framework is loss monitoring: determining if there are any signs of nutrient loss due to volatilization, runoff, leaching or other means, and adjusting your management accordingly.

Finally, the fifth stage of the framework is carbon assessment: comparing the estimated CO_2e from the fertilizer management strategy to a baseline estimate and reporting both environmental and production results. Conceptually speaking, the framework can be viewed as: Crop requirement + Soil condition → Optimal fertilizer strategy → Application efficiency → Decrease in nutrient loss → Increase in nutrient-use efficiency → Decrease in carbon footprint. The above analysis demonstrates each part of the framework at a descriptive level; however, it does not independently measure every intermediate mechanism. The most robust empirical component of the above analysis is the recurring relationship between fertilizer-loss levels and Total CO_2e, followed by the consistent CF > OF pattern under the comparison of fertilizer treatments. A framework such as this avoids an oversimplistic recommendation to substitute one form of fertilizer for another. Organic fertilizer may have environmental benefits under some circumstances; however, its life-cycle performance is influenced by sourcing, processing, storage, transportation and nutrient content. Likewise, chemical fertilizers are essential sources of nutrients for crops and may promote high levels of productivity when used effectively.

Consequently, the more general principle supported by the above analysis is efficient and site-specific nutrient management rather than a universal input substitution rule. For researchers, this framework provides a clear path for expanding data sets. Researchers should include fertilizer quantity, nutrient composition, application timing, soil moisture content, soil organic carbon content, crop yield and measured nutrient losses in their subsequent observations along with the methodology employed to estimate CO_2e. Including these additional variables will enable researchers to differentiate between correlative mechanisms and causal mechanisms, as well as to evaluate emissions on a yield-scaled basis. The resulting database can support various analytical methods including regression, factorial ANOVA, mixed-effects models or machine learning algorithms depending on the size of the sample and study design. For policymakers, this framework indicates that reducing nutrient losses should receive explicit recognition within agricultural climate strategies. Improving nutrient-use efficiency can potentially reduce wasteful inputs while maintaining productivity.

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However, policymakers should base their decisions on evidence-based research and consider the uniqueness of local farming systems. Incentives for soil testing, precision nutrient management, improved application technologies, enhanced-efficiency fertilizers and farmer education may be more successful when combined with monitoring of actual nutrient-use outcomes instead of only considering the quantity of fertilizer purchased or applied.

4.20 Interpretation of the Relative Importance of the Factors

The integrated results indicate that the factors analyzed do not account for variations in observed CO_2e in the same manner. Crop type establishes a large range around which emissions occur. Fertilizer treatment produces a systematic difference between chemical and organic fertilizer categories. Soil type creates small differences in the direction of which varies among different combinations.

On the other hand, fertilizer-loss level produces a repetitive and relatively large gradient from low to medium to high. As such, managing nutrient losses should receive particular attention in future modeling and field validation studies. The relative importance presented above should not be translated directly into causal statements. The above dataset did not contain a randomized intervention study in which fertilizer loss was experimentally manipulated while all other factors were kept constant.

Therefore, the above analysis is best characterized as descriptive and associative. Nonetheless, the strength of a repeating pattern across 45 crop–soil–loss combinations represents a valuable empirical signal. It represents a relationship that can be investigated statistically in future research and can serve as a guide for selecting variables for a more comprehensive carbon footprint model. The results also illustrate the importance of analyzing interactions. A comparison of single factors may show that rice has greater emissions or that organic fertilizer results in lower emissions; however, it would not indicate whether the fertilizer-loss pattern remains consistent across soils and crops. The three factor dataset illustrates that the Low < Medium < High ordering remains consistent across all combinations. This consistency is significant because a management strategy that performs consistently across diverse crop–soil environments may have broader applications if validated through field studies. Collectively, the evidence indicates a systems perspective where carbon emissions from agriculture are influenced by crop characteristics, soil context, fertilizer source and nutrient-use efficiency. Converting descriptive patterns into statistically testable relationships and acquiring additional agronomic data (specifically fertilizer rate, yield and measured nutrient losses) represent the immediate priorities for further investigation. Acquiring this information will enable researchers to quantify the carbon footprint not only as Total CO_2e but also in relation to agricultural production and resource efficiency.

5. DISCUSSION

5.1 Fertilizer loss as the dominant descriptive gradient

The central result is the stability and magnitude of the fertilizer-loss gradient. Across 45 observations, the average increase from low to high loss is about 99.34 CO_2e units. The effect is repeated across all crop and soil categories. Compared with the relatively small differences among soil means, fertilizer-loss level represents the most prominent descriptive source of variation in the supplied dataset.

A plausible pathway is that greater fertilizer loss represents poorer nutrient-use efficiency. Nutrients that are not retained or taken up by crops may require compensatory inputs, increasing the upstream and downstream environmental burden of fertilizer use. This interpretation is consistent with nutrient-use-efficiency research [5, 8, 17] and with evidence that nitrogen losses and greenhouse-gas emissions are linked to fertilizer management [1, 21, 28]. It remains a hypothesis in this study because nutrient-use efficiency and individual emission pathways were not directly measured.

5.2 Interpreting the CF > OF pattern

The consistent lower emission values under organic fertilizer provide a second important management signal. The result is compatible with research showing that fertilizer production and use can have different emission profiles [13, 23, 36]. Synthetic nitrogen production is energy-intensive, and field application can generate direct and indirect emissions. However, organic fertilizers can also generate emissions during processing, storage, transport and field decomposition; therefore, the comparative result depends on the system boundary and material source [36, 38].

The appropriate interpretation is consequently not 'organic fertilizer is always better', but rather 'organic fertilizer is associated with lower emission values under the conditions represented in the supplied dataset.' A full sustainability assessment should also include yield, nutrient supply, soil health, economic feasibility and transport requirements. This is particularly important because replacing a nutrient source without matching crop demand can create new inefficiencies.

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5.3 Crop-specific mitigation

The results suggest a targeted rather than uniform mitigation strategy. Rice has the highest baseline emission level and also shows the greatest reported absolute reduction between chemical and organic fertilizer. Corn similarly has a relatively high baseline and substantial reduction potential. Such crops can be prioritized for improved nutrient management, but the same loss-reduction principle applies to all five crops because the Low < Medium < High pattern is universal in the supplied data.

This finding agrees with climate-smart and sustainable-intensification approaches that emphasize combinations of practices rather than a single intervention [3, 12, 19, 24, 30, 31]. Site-specific nutrient management and decision-support systems can improve input efficiency [7, 34], while enhanced-efficiency fertilizers can reduce nutrient losses in appropriate contexts [6, 37].

5.4 Relationship to wider emission evidence

The magnitude of the fertilizer-loss gradient should not be interpreted as a direct estimate of a particular greenhouse gas. Total CO_2e is an aggregate indicator, whereas agricultural emissions include CO_2, CH_4 and N_2O with different sources and controls [2, 26, 29]. Global studies show that fertilizer-related emissions arise across production and field-use stages [23, 35]. Therefore, the present analysis is best understood as identifying a pattern in the supplied CO_2e indicator that warrants mechanistic validation.

The study is also consistent with the broader evidence that agricultural mitigation depends on improving resource efficiency. Sustainable intensification and climate-smart agriculture emphasize producing food while reducing environmental burdens [3, 12, 24, 31]. The 4R framework provides a practical bridge from this evidence to management by linking nutrient source, rate, timing and placement [9, 15].

6. SUSTAINABILITY AND POLICY IMPLICATIONS

The combined results support a practical pathway: appropriate fertilizer selection + improved application efficiency + reduced fertilizer loss → improved nutrient-use efficiency → potentially lower carbon footprint. The policy objective should not be to minimize fertilizer use indiscriminately, because crops require adequate nutrients for productivity. Instead, the emphasis should be on supplying the right nutrient in the right amount, at the right time and in the right place [9, 15].

First, nutrient recommendations can be made more crop-specific. High-emission crops such as rice and corn may offer substantial opportunities for absolute reductions. Second, fertilizer-loss monitoring should be incorporated into nutrient-management programs. Third, soil testing and soil-sensitive application can help match nutrient supply with retention and crop demand. Fourth, decision-support tools and enhanced-efficiency products can be evaluated where they improve nutrient-use efficiency [6, 7, 37].

Policy should also recognize uncertainty in fertilizer carbon footprints. Life-cycle emission factors vary across production systems and organic-material sources [36, 38]. Incentives should therefore reward measured or credibly estimated improvements in nutrient-use efficiency rather than assuming that one fertilizer category is automatically low-carbon. This is consistent with an overall climate-smart strategy which integrates mitigation efforts with increased productivity and enhanced resilience at all levels of the food system [18].

At the farm level there are several practical ways farmers can implement 4R strategies. Some examples include: (1) minimizing over-application, (2) optimizing both the time of application and the location of application, (3) using soil test data to determine the appropriate rate of fertilizer application, (4) tracking whether nutrients are being lost from the soil, (5) assessing potential benefits or risks associated with different types of fertilizers based upon their impact on the entire ecosystem. Extension programs can also help producers understand how to utilize 4R strategies; research programs can also combine on-site measurement of emissions with the calculation of the carbon footprint of production systems.

7. LIMITATIONS AND FUTURE RESEARCH

The limitations of this descriptive study affect how the results can be interpreted. First, there are no inferential statistics (e.g., p-values), confidence intervals, or formal estimates of the effects of factors (factorial analysis). Second, the study has a lack of causal inference.While we find a positive correlation between the highest level of fertilizer loss and higher CO_2e, we cannot say if fertilizer loss itself was responsible for this increase. Third, we did not measure nutrient-use efficiency, fertilizer rate, yield, weather, irrigation, N_2O, CH_4, CO_2 fluxes or life-cycle stage individually. Fourth, the comparison of organic versus conventional fertilizers is based solely on the CF/OF analysis provided by the supplier.

Therefore, our findings should not be applied outside of their system boundaries. The effectiveness of organic fertilizers can vary depending upon their source, method of production, nutrient composition and application technique. Fifth, the categorical loss levels used in the study do not allow us to determine the continuous relationship between the amount of fertilizer lost and the amount of emissions produced. Future research will need

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to develop a factorial model that includes crop type, soil properties, fertilizer treatment, loss level and any potential interactions among these variables. Once this model is developed, researchers will be able to calculate the magnitude of the effects of each variable and estimate the range of variability in those estimates (uncertainty). Future research will also need to collect continuous measurements of fertilizer rate, nutrient balance, yield, water management and weather conditions.

Additionally, future research will need to combine field measurements of N_2O, CH_4 and CO_2 with Life Cycle Assessments (LCAs) to understand what processes are contributing to the observed patterns. Finally, future research will need to conduct scenario analyses to evaluate how different mitigation strategies will perform when considering the trade-offs between agricultural productivity and economic viability.

8. CONCLUSION

The results of this study show three consistent descriptive relationships. First, there was a direct relationship between the amount of fertilizer applied (total CO_2e) and the amount of fertilizer lost. Average emissions increased from approximately 232.63 at low loss levels, to approximately 282.25 at intermediate loss levels, and to approximately 331.97 at high loss levels. There was an average increase in emissions of approximately 99.34 CO_2e units from the lowest level of loss to the highest level of loss. This trend was observed for each of the five crops studied and for each of the three different soil types. Secondly, there were large differences in baseline emission rates among the various crop types. For example, rice had the highest average emission rate, while vegetable crops had the lowest average emission rate. There were relatively small differences in emission rates based upon soil type; however, the data did not provide evidence to support the idea that sandy soils always had the highest emission rates. Third, the supplied analysis on fertilizer treatment demonstrated a consistent CF > OF relationship among the crops evaluated. The largest absolute reduction in emissions due to fertilizer treatment occurred with higher-emission crops such as rice and corn.

Therefore, these results indicate that a combination of selecting appropriate fertilizers, increasing nutrient-use efficiencies, and decreasing fertilizer loss will likely result in the greatest overall decrease in emissions. One major scientific concern regarding the results presented here is that they are correlational. They do not demonstrate cause-effect relationships or indicate which specific processes cause increased emissions. However, the consistency of the patterns observed in the data could serve as an important empirical foundation for future studies involving factorial modeling, uncertainty analysis, field validation studies, and life cycle assessments.

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