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Deviation From the Regression of Yield on Nitrogen Fertiliser Rate as a Tool for Detecting Fraud in Organic Banana Production

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ABSTRACT

Background and aims: Bananas are demanding in nitrogen (N) input; therefore, there is a temptation for organic farmers for using synthetic N fertilisers, which are not allowed under organic standards. The aim of our study was to develop a tool that identifies high banana yields obtained with suspiciously low organic N input.

Methods: We systematically reviewed literature from experimental studies on N fertilisation in bananas from all over the world. We also developed a simplified N balance model for organic bananas. Furthermore, N fertilisation and banana yield data from organic and conventional farmers in different countries were collected. From these, a subset of trustworthy organic farms was identified, as a reference concerning plausible ratios of yield versus fertilisation. A model was developed to estimate the deviation from the regression of trustworthy farms and thus identify suspicious cases.

Results: Neither literature nor the N balance led to a meaningful benchmark for differentiating plausible from non-plausible yields. The regression of yield on N fertiliser rate from the trustworthy organic farmers, however, turned out to be a helpful reference, and the deviation from this regression helps to achieve our aim. Depending on the alert limit, that is, the probability of obtaining false positive results, 4, 6, or 9 out of 157 data-pairs from organic farmers turned out to be suspicious.

Conclusion: Measuring deviation from the regression of the trustworthy farms is a useful tool for identifying organic banana farmers suspected to be using synthetic N fertilisers but is not in itself a proof of fraud. The model will improve as more data becomes available.

1 | Introduction

As opposed to real tree crops, a new banana plant grows from a sucker of the mother plant in every cycle, which requires high nutrient inputs, especially of nitrogen (N) and potassium (K) (Dorel et al. 2023; Lima de Deus et al. 2020; Weinert and Simpson 2016). While mineral K-fertilisers from mined sources of potassium sulphate are allowed by organic standards, this is not the case for non-organic (synthetic) N-fertilisers (CFR Part 205 2025; European Union 2023). These are prohibited with the purpose of minimising environmental damage, such as high fossil fuel use for fertiliser production, ammonia and nitric oxide emissions as important causes of global warming, ecosystem eutrophication and nitrate contamination of water bodies (Udvardi et al. 2015).

The majority of N accumulated by a banana plant is recycled through the decomposition of plant material; only 25%–30% of the total N accumulated is exported from the farm (Zhang et al. 2019). In studies by Prasertsak et al. (2001), this rate was even as low as 10%. In general, biological N_2 fixation (BNF) is expected to be the most important source of N in organic farming (CFR Part 205 2025; European Union 2023), but so far, legume cover crops have been implemented in commercial banana production mostly at an experimental level (Espindola et al. 2006; CIRAD 2025; Damour et al. 2014; Ocimati et al. 2021; Ripoche et al. 2012; Tixier et al. 2011).

On the other hand, several authors found a close correlation between soil organic matter (SOM) content and banana yields (Rondon et al. 2021; Sun et al. 2020; Villarreal-Núñez et al. 2013), suggesting that SOM may be a relevant source of N, especially after converting perennial grassland or forest to banana plantations. According to Qin et al. (2021), however, approximately seven years after converting natural forests to banana plantations, N mineralisation stabilises at a lower level, meaning that such 'natural' N sources are available only during a relatively short period and are not sustainable. Such a 'soil-mining' approach would contradict one of the fundamental principles of organic farming: "*organic production shall [...] be based [...] on (a) the maintenance and enhancement of soil life and natural soil fertility, soil stability, soil water retention and soil biodiversity, preventing and combating loss of soil organic matter, soil compaction and soil erosion, and the nourishing of plants primarily through the soil ecosystem*" (European Union 2023).

Most banana farms are specialised operations that do not have livestock and therefore do not have their own farmyard manure as a source of N. N supply in commercial organic banana plantations therefore mostly relies on commercial organic fertilisers with relatively high N concentration, made from guano, dried poultry manure, slaughterhouse by-products, algae extracts and so forth. These are typically more expensive than synthetic N fertilisers, which may create a temptation to use synthetic N fertilisers.

To protect the integrity of the organic market, the European Commission (2021) requires organic certification bodies to identify the 'risk of non-compliance' for the operators they certify. Other organic programmes have similar requirements for certifiers. Use of synthetic N fertilisers is one of the major risks for organic compliance. The purpose of the present study is to develop a compliance screening method for detecting the use of synthetic N fertilisers in organic banana production.

2 | Materials and Methods

2.1 | Fertiliser Prices

To verify if the assumption of higher prices for organic fertilisers is correct, in April 2024, we obtained prices for organic and synthetic N fertilisers from a farm input store in Machala, in the centre of one of the banana growing regions in Ecuador.

2.2 | Literature on Experimental Studies

Using the search terms 'organic banana production', 'nitrogen fertilisation banana yield', 'nitrogen fertiliser banana production', 'nitrogen input banana' and 'nitrogen efficiency bananas', as well as their Spanish translations, we searched the database of the online library of the University of Kassel, Scopus, ScienceDirect, ResearchGate, Musa Lit (2024) and Google Scholar. We excluded all studies (1) dealing with bananas grown under subsistence farming conditions or with highland bananas, (2) related to plantain or dwarf bananas, (3) that did not allow to establish a clear link between N_f and Y and (4) with treatments using more than 500 kg N ha^{-1} y^{-1}, because this was the upper limit of the commercial farm data we were provided (Figure 5a,c). Where experiments included several treatments with the same N_f rates (but, e.g., different K fertilisation or water supply rates), we excluded those treatments where the other factor was obviously limiting, and for the remaining treatments, we used the average of the yields obtained for the same N_f rate.

From a total of 206 studies reviewed, 141 were excluded for the reasons mentioned above, whereas 65 studies with a total of 326 data-pairs (Y/N_f) were considered for regression analysis. These came from 22 countries, India (12), Brazil (11), Ecuador (8), Colombia (6) and China (5) being the most important ones. It turned out that data are extremely scattered, so that, for example, for the range from 150 to 200 kg N ha^{-1}, yields can be as low as 16.25 t ha^{-1} (Caballero et al. 2004), or as high as 82.5 t ha^{-1} (Meya et al. 2023). The quadratic model fitted across the 250 and 76 data-pairs for synthetic and organic fertilisation showed a coefficient of determination (R^2) of only 0.12 and 0.19 for conventional and organic fertilisation, respectively (Figure S1). This large variance is probably caused by very different climatic and soil conditions, management, irrigation, impact of pests and diseases, experimental set-ups and scientific rigour. In some studies, there may also be confusion between annual yield and yield per production cycle, which is shorter than one year in most banana producing areas. Furthermore, only 5 out of the remaining 65 studies included error indicators in their results, which would be required for a statistically sound meta-analysis (Madden et al. 2016).

We therefore abstained from using data from these studies as a reference for the commercial farm data, except for results from Aguilar (2019), Oña (2014) and Pattison et al. (2018), obtained under conditions that were comparable to commercial banana production.

2.3 | Data Collection

We approached banana farmer organisations, organic farmer associations, state authorities in the banana sectors, farm advisors and certification bodies for data concerning banana yield versus N fertilisation in commercial production. We received data from two organic certification bodies, one organic farmer association, two farm advisors and several individual farms. In total, we obtained

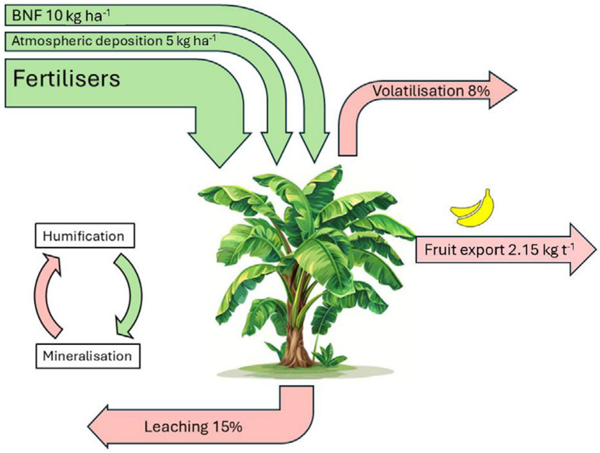


FIGURE 1 | Simplified N cycle for organic banana farms. Inputs are in green colour, outputs in red colour. Humification is a 'loss' only in the short term because humified N is not readily available for the crop. In the long term, humification increases soil fertility. BNF, biological N_2 fixation.

data from 93 organic and 33 conventional farms from Ecuador, Dominican Republic, Costa Rica, Colombia, Ghana, Guatemala, Honduras, Panama and Peru. Ecuador and Dominican Republic accounted for 53% and 22% of data, respectively (Table S1).

2.4 | Case Study: Two Organic Farms

A separate evaluation was done for two banana farms, Hacienda Paso Roble and Quinta Pasadena from Dominican Republic, which kindly provided us data over a period of approximately 10 years, as well as soil analyses done by A&L Great Lakes Laboratories Inc. Out of the different soil indicators tested by this laboratory, we only used SOM, which seems to be the most relevant one in relation to N supply (see A&L Great Lake Laboratories Inc. (2025) for a description of soil testing methods).

2.5 | N Balance

A possible approach for detecting non-plausible ratios between N_f and Y is through a simplified N balance, that is, a farm-gate balance excluding most of the internal recycling processes (Figure 1). We have used the assumptions explained in Table 1 for this purpose.

Assuming that mineralisation and humification are balanced, the general model would be

$$\text{Balance} = N_f + \text{BNF} + \text{Deposition} - \text{Volatilisation} - \text{Leaching} - Y. \quad (1)$$

Plugging in the assumptions from Table 1 takes us to the hypothetical equation:

$$B = N_f + 10 + 5 - 0.08N_f - 0.15N_f - 2.15Y. \quad (2)$$

This is also depicted in Figure 1.

Using these considerations, total ***assumed*** N losses (L_a) would be:

$$L_a = 0.23N_f - 15. \quad (3)$$

N_f here is multiplied by 0.23 because of 8% volatilisation and 15% leaching losses, whereas 15 kg N ha^{-1} are assumed to be replaced by BNF plus atmospheric deposition and therefore subtracted from the losses.

We verified if these figures are in line with losses defined as the difference of N_f minus N removal via banana harvest, calculated from the commercial farm data, here called ***real*** N loss (L_r):

$$L_r = N_f - 2.15Y. \quad (4)$$

2.6 | Deviation From the Regression

The analyses in this part were done in SAS. The SAS code is published in the Supporting Information section. In our dataset from 126 farms, the 33 conventional farms showed a response curve for Y on N_f that was significantly different from the 93 organic farms (Figure S3). To avoid these interactions, we excluded the conventional data and concentrated on the organic ones only.

The challenge with this reduced dataset is that there is limited assurance that organic farmers have strictly adhered to the requirements for N fertilisation (N_f). Some of them may have used additional, undeclared fertilisers. Therefore, we identified a subset of farms, for which we have no doubt concerning the integrity of their data because they have a long-standing history of compliance, repeatedly verified by competent independent inspectors. This subset of farms includes 27 farms, among these the on-farm experiments by Aguilar (2019) and Oña (2014), and the above-mentioned 2 farms from Dominican Republic, with a total of 64 data-pairs. This subset of 27 farms is called 'trustworthy' in the following, whereas the remaining 66 farms, with a total of 93 data-pairs, are called 'other' farms.

Using the trustworthy farm data, we fitted a quadratic model for the response of Y (in t ha^{-1} y^{-1}) to N_f (kg ha^{-1} y^{-1}) of the form:

$$\eta\left(N_f\right) = \beta_0 + \beta_1 N_f + \beta_2 N_f^{\,2} \quad (5)$$

This model was subsequently reduced by dropping the quadratic term, which was not significant. To account for the fact that some trustworthy farms provided more than one treatment mean, and some of them for multiple years, we added a random farm effect and a random farm by unit effect to the linear predictor. Moreover, we fitted a serial correlation across years at the unit level, using an AR(1) model, where unit refers to the area having received the same fertiliser treatment in a given year. On the basis of the fitted model, we computed standardised residuals using the following equation:

$$r = \frac{Y - \hat{\eta}\left(N_f\right)}{\sqrt{\text{var}\left[\hat{\eta}\left(N_f\right)\right] + \hat{\sigma}_s^2 + \hat{\sigma}_{sa}^2 + \hat{\sigma}_e^2}}, \quad (6)$$

TABLE 1 | Assumptions for conducting a preliminary N balance for organic banana production, using conservative estimations for all output data.

Pathway	Input/Output	Range	References	Comment	Preliminary assumption
Atmospheric deposition	Input	3 kg N ha^{-1} y^{-1} (Cuba) 3–7 kg N ha^{-1} y^{-1} (Ecuador)	Borbor-Cordova et al. (2006), González-De Zayas et al. (2012)	Atmospheric N deposition is high in countries with a high number of vehicles km^{-2} and a high stocking rate of livestock. Neither of the two applies to most banana producing countries, with the exception of India and China (Vishwakarma et al. 2023; Xu et al. 2023)	5 kg N ha^{-1} y^{-1}
Biological N_2 fixation (BNF)	Input	0–20 kg N ha^{-1} y^{-1}	Herridge et al. (2008)	According to this meta-study, the average worldwide BNF rate by non-symbiotic (i.e., the combination of endophytic, associative and free-living) bacteria on crop land is below 5 kg N ha^{-1} y^{-1} (excluding sugarcane). To this, we add 5 kg N ha^{-1} y^{-1} from spontaneously growing legumes	10 kg N ha^{-1} y^{-1}
Export of N through harvest	Output	1.66–3.0 kg N t^{-1} bananas (mean 2.15 kg N t^{-1})	Jeyabaskaran et al. (2018), Langenegger and Smith (1988), Malburg and Lichtemberg (1986), Moreira et al. (2010), Nomura et al. (2017), Prasertsak et al. (2001), Teixeira et al. (2007), Xu et al. (2023), Zucoloto et al. (2023)	We use the mean value of 2.15 kg N t^{-1} banana (0.215%)	2.15 kg N t^{-1}

(Continues)

TABLE 1 | (Continued)

Pathway	Input/Output	Range	References	Comment	Preliminary assumption
Leaching (NO_3^-)	Output	13.6%–63%	Armour et al. (2013), Haas et al. (2002), Huddell et al. (2020), Muñoz-Carpena et al. (2002)	Leaching increases with N input, precipitation/irrigation, low SOM, low capacity of plants for taking up N and sandy soil texture. In general, leaching is lower when organic fertilisers are used	15% of N_f
Volatilisation (NO_x and NH_3)	Output	6.4%–27.4% of applied N	Huddell et al. (2020), Prasertsak et al. (2001), Rocha et al. (2019), Veldkamp and Keller (1997)	In a meta-study, Huddell et al. (2020) found an average of approx. 8% of N_f volatilisation in tropical cropping systems, when 100 kg N ha^{-1} y^{-1} were applied, with a very large variance. Absolute amounts increased with increasing N input, whereas percentage decreased slightly. As N input in organic banana production is generally on the lower side, we use 8% here	8% of N_f
Humification/Mineralisation	—	—	—	We assume here that mineralisation and humification should be balanced, as a minimum. The goal is that humification should be higher than mineralisation. A 'soil-mining' system, where SOM decreases steadily over the years, would be a violation of organic farming standards	—

Abbreviation: SOM, soil organic matter.

where Y is the observed response, $\hat{\eta}(N) = \hat{\beta}_0 + \hat{\beta}_1 N_f$ is the predicted value, $\mathrm{var}[\hat{\eta}(N_f)]$ is the estimated variance of the prediction, $\hat{\sigma}_s^2$ is the estimated variance of the farm effects, $\hat{\sigma}_{sa}^2$ is the estimated variance of the farm-by-year effects, and $\hat{\sigma}_e^2$ is the estimated error variance of the fitted linear mixed model. The prediction variance is given by

$$\mathrm{var}\left[\hat{\eta}\left(N_f\right)\right] = \mathrm{var}\left(\hat{\beta}_0\right) + 2N_f \mathrm{cov}\left(\hat{\beta}_{0,}\hat{\beta}_1\right) + N_f^2 \mathrm{var}\left(\hat{\beta}_1\right), \quad (7)$$

where $\mathrm{var}(\hat{\beta}_i)$ $(i = 0, 1)$ is the variance of $\hat{\beta}_i$, and $\mathrm{cov}(\hat{\beta}_0, \hat{\beta}_1)$ is the covariance of $\hat{\beta}_0$ and $\hat{\beta}_1$. The standardised residuals are assumed to have an approximate standard normal distribution for observations from farms that report N_f correctly. Farms for which $r > t$ for some positive threshold t may be flagged as suspicious. Here, we set $t = 1.96$, corresponding to the 97.5% quantile of the standard normal distribution, meaning that a farm operating in accordance with the rules stands a chance of 2.5% of being erroneously flagged as suspicious. We further also used thresholds at 5% and 10% levels of error probability, that is, $t = 1.64$ and $t = 1.28$, respectively. The threshold t on the standardised residual in Equation (6) is translated into a threshold on the observed response Y for given level N_f. The plot of these thresholds versus N_f is a curve located above the fitted regression line in the direction of the vertical axis.

Congreves et al. (2021) list 22 different definitions of N use efficiency. Out of these, we use the partial factor productivity (PFP) here, defined as the yield per unit of fertiliser applied (kg bananas per kg N_f, in the following kg ban. kg^{-1} N_f), because this definition requires only the variables N_f and Y. PFP may be obtained from the quadratic model (1) for yield as

$$\mathrm{PFP}\left(N_f\right) = \frac{\eta\left(N_f\right)}{N_f} = \frac{\beta_0}{N_f} + \beta_1. \quad (8)$$

Furthermore, we obtained soil test results from 50 of the 126 farms, done by different private, government and university laboratories. Much of the data, however, turned out to be inconsistent and not plausible; therefore, we could not use it for statistical analyses.

3 | Results

3.1 | Fertiliser Prices

The price per kg N of organic fertilisers was found to be 4.9–7.5 times higher than synthetic fertilisers (Figure 2a). Therefore, there is a financial temptation for organic farmers to use fertilisers that are noncompliant with organic standards, as sometimes confirmed by visual evidence especially during unannounced inspections (Figure 2b–e).

3.2 | Literature on Experimental Studies

The high variance of yield response to N rate in different countries and growing conditions precluded using these data as a reference for the commercial farm data. We found, however, that there are no major differences between the mean values of the Y/N_f ratio

FIGURE 2 | (a) N concentration and farm input store prices per kg N for two synthetic and five organic N fertilisers in Machala, centre of one of the Ecuadorian banana growing regions, as of April 2024. (b and c) Ammonium sulphate bag and fertiliser on the ground found during an unannounced inspection to an organic banana farm. (d) Hole in pseudostem of the mother plant, opened with a machete for injecting urea dissolved in water. (e) Adapted knapsack sprayer for injecting urea. *Source:* Pictures with permission from an organic farm inspector.

of organic and synthetic N fertilisation. The quadratic regression lines for both fertilisation forms are similar (Figures S1 and S2).

In a long-term experiment by CIRAD (2025) in Martinique, however, the average PFP over 6 years for organic fertilisation is 106.4 kg ban. kg^{-1} N_f (applying 514 kg ha^{-1} y^{-1}), whereas for synthetic fertilisation, it is 159.5 kg ban. kg^{-1} N_f (applying 440 kg ha^{-1} y^{-1}) (personal communication from C.-M. Rohe; CIRAD 2025).

3.3 | Case Study: Two Organic Farms

A more detailed investigation of two individual organic banana farms in Dominican Republic provides interesting insight

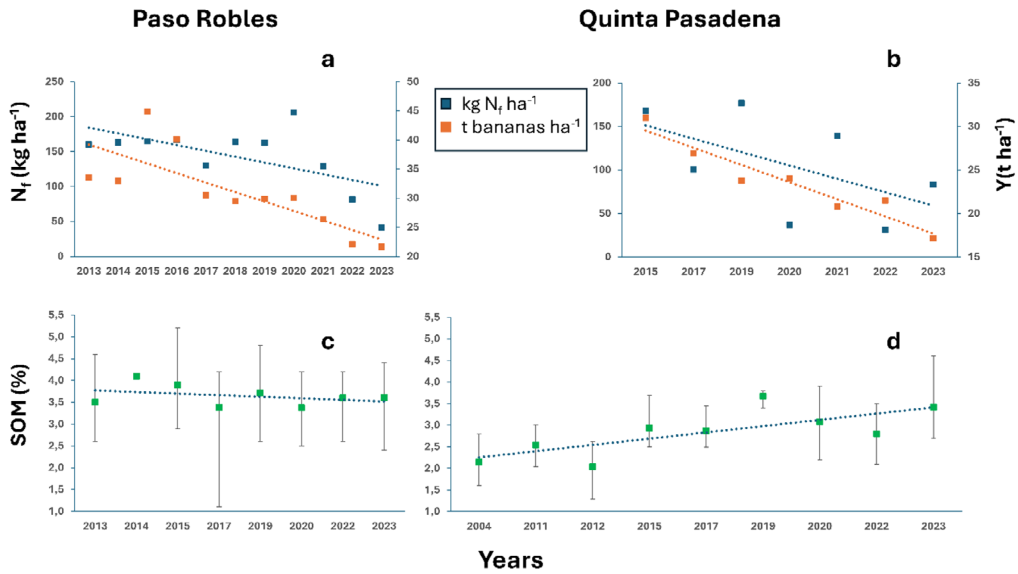


FIGURE 3 | (a and b) Development of banana yield and N fertilisation over approx. ten years on two of the trustworthy organic farms in Dominican Republic. The farms started reducing N_f after joining private organic certification programmes that restrict total N_f in 2020. Parts (c and d) show development of soil organic matter on the same farms (mean, maximum and minimum values from different fields). The x-axis in (d) starts earlier because SOM data are available from 2004 on, whereas fertilisation and yield data are available only from 2015 on. Note the different scales of the y-axes in (a) and (b). SOM, soil organic matter.

(Figure 3). The two farms reduced N_f since 2020 because they joined private organic programmes whose standards allow only very low external N_f. Consequently, the per-hectare yield has decreased in parallel—although SOM and residual nitrogen reserves seem to be able to buffer changes in fertilisation, as, for example, on Quinta Pasadena in 2020 and 2022 (Figure 3b). SOM on Paso Robles has been, more or less, stable over these years (Figure 3c), whereas on Quinta Pasadena, it has increased substantially (Figure 3d). Therefore, looking at this case study, it is highly unlikely that N nutrition in organic banana production in the long run would be based on soil mining. On the contrary, a substantial part of applied N may have gone into building up or being bound in SOM.

3.4 | N Balance

One way to understand N balancing is by examining N losses. The assumptions concerning N input and output explained in Table 1 and Figure 1, and summarised in Equation (3), yield a line with a relatively modest slope (L_a in Figure 4). In contrast, ‘real’ N losses for our 126 farms, defined simply as the difference between N_f and N removed through banana harvest (L_r, see Equation 4), have a much steeper slope for all three subsets of data (conventional, trustworthy organic, other organic). The assumptions from Table 1 concerning leaching, volatilisation, deposition and BNF grossly underestimate the amount of N ‘lost’ in the system, when more than approx. 100 kg N ha^{-1} are applied. Losses through leaching and/or volatilisation may be higher than assumed, but probably a substantial part of N_f applied in the form of organic fertilisers is not lost but rather contributes to increasing SOM, as has been found in many long-term studies (e.g., Fließbach et al. 2007; Nardi et al. 2004; Paul et al. 2003).

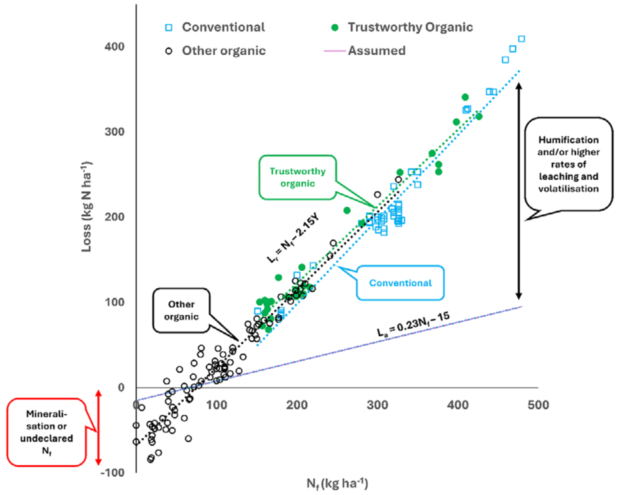


FIGURE 4 | Assumed (L_a) versus real (L_r) N loss: L_a is based on general assumptions concerning percent of N losses through leaching and volatilisation (23%) and input from atmospheric deposition and BNF (15 kg N ha^{-1}) (see Table 1 and Equation 3). L_r is based on the definition of ‘loss = N_f–N removal through harvest’ (Equation 4), for the dataset, we have gathered. In this figure, we have included previously excluded data from conventional farms to show that N losses according to the latter definition tend to be slightly lower for conventional than for organic production, whereas the overall trendlines are very similar for the three farm groups. The gap between L_a and L_r (black arrow on the right side) can either be explained by humification (N is used for building up SOM, or bound in SOM), and/or higher losses through leaching and volatilisation than assumed in L_a. The negative values (red arrow on the left side), where N_f does not even compensate the N removal through harvest, without considering leaching and volatilisation, may be explained by N supply through short-term mineralisation of SOM, or through undeclared N_f.

3.5 | Deviation From the Regression

For N_f and Y data from 93 organic farms (see Table S1), parameters and coefficients for the fitted model (Equation 5) were estimated as follows:

β_0	23.3842
β_1	7.6552×10^{-2}
σ_s^2	44.977
σ_{sa}^2	4.716
σ_e^2	43.046
ρ	0.596
$\mathrm{var}(\hat{\beta}_0)$	7.209
$\mathrm{var}(\hat{\beta}_1)$	1.710×10^{-4}
$\mathrm{cov}(\hat{\beta}_0, \beta_1)$	-2.697×10^{-2}

Both parts (a and c) of Figure 5 show that the regression line for trustworthy farms lies slightly below the position we would expect for a function representing ***all*** data. Depending on the alert limit, which in turn depends on the chosen probability of having false positive results (2.5%, 5% or 10%), four, six or nine farms, respectively, are identified as suspicious (Figure 5b,d), one of these being a false positive result (Figure 5e).

For identifying suspiciously high banana yields produced with very low N fertilisation, based on our analyses, the following equations can be used:

$$\hat{\eta}\left(N_f\right) = 23.3841 + 7.6552 \times 10^{-2} \times N_f, \tag{9}$$

$$\mathrm{var}\left[\hat{\eta}\left(N_f\right)\right] = 7.209 - 2.697 \times 10^{-2} \times N_f + 1.710 \times 10^{-4} \times N_f^2, \tag{10}$$

$$r = \frac{y - \hat{\eta}\left(N_f\right)}{\sqrt{\mathrm{var}\left[\hat{\eta}\left(N_f\right)\right] + 99.74}}. \tag{11}$$

In Table S2, readers find an Excel template for entering their N_f and Y values into these equations.

4 | Discussion

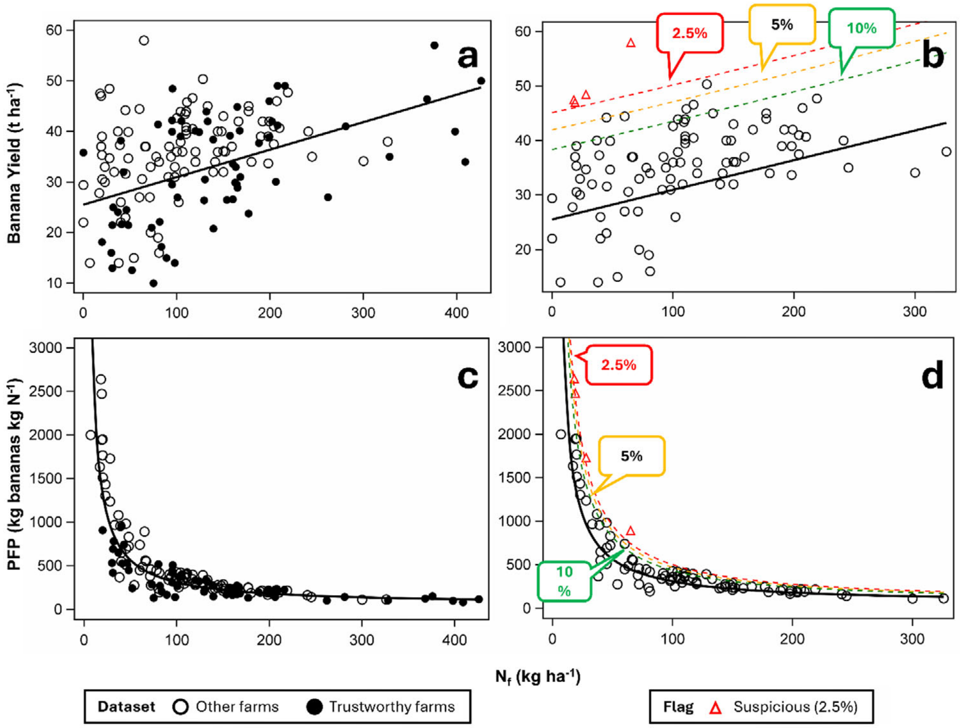
There is an enormous variance in banana yield response to N fertilisation because N_f is only one out of many variables affecting banana yields. Under certain conditions, soil (e.g., K availability, SOM, biological activity, pH, salinity and bulk density), weather (e.g., water availability, temperature and hurricanes), diseases and pests (e.g., sigatoka and thrips) and management (e.g., planting density and sucker management) may be more important than N_f. A certification body, however, is normally not able to conduct a complex multi-factor study; therefore, the approach of using one single relevant, and often limiting, variable offers a practical tool, which is relatively simple to handle.

It would be too simplistic if we were to speak of fraud as soon as the assumed N-balance turns negative, especially when we consider that the assumed outputs (Figure 1) do not accurately reflect the actual situation on the farms (Figure 4). Time is an essential aspect for correct interpretation of banana yield response to N fertilisation. As reflected in Figure 3, especially (b), SOM can serve as an N reserve over a short period, especially when the soil is rich in SOM and is biologically active. This is also reflected in some of the literature, where yields above 40 t ha^{-1} y^{-1} were obtained in 0 N_f treatments (e.g., Lin et al. 2021). There is no evidence, however, that this would be possible during more than one year. Due to the possible short-term buffer function of SOM, high banana yields with low N_f in one year should raise suspicion. For confirming the suspicion, however, the situation should be observed over two or better three years, if there is no evidence of fraudulent practices found during unannounced farm inspections (see, e.g., Figure 2b–e). Anonymous whistleblowers from the banana industry have reported that recorded fertiliser applications often exist only on paper. In some cases, farm input stores even seem to sell organic fertilisers to a farm, so that inspectors can confirm the existence of bags and invoices, after the inspection buy the fertilisers back from the farm, and subsequently sell the same sacks to several farmers. Such practices can, of course, not be detected through a statistical tool, but only by professional, integer and unannounced inspections.

Low ratios of $^{15}N/^{14}N$ isotopes can also confirm such a suspicion. For this purpose, a large number of representative fruit samples from the suspicious farm are needed, as well as a large number of samples from a conventional farm in the same region, with similar soil conditions, for establishing a reliable benchmark (Tixier et al. 2022).

We dropped the quadratic term from our Y to N_f model because it was not significant. As a result, we see a modest linear increase in Y with increasing N_f (Figure 5a,b). This is because the highest N_f we have found on commercial organic farms was 450 kg ha^{-1}. We would expect the response curve to show an asymptotic or quadratic shape at higher fertilisation rates as factors other than N_f become limiting (Dhakal and Lange 2021). It is worth stressing that there is a large between-farm variance (σ_s^2), and this is fully captured and represented by our procedure. The relatively large width of the tolerance interval to a large part results from this large variance, and it must be acknowledged that the large width of the interval adversely affects the power to detect fraudulent cases.

Several organic banana farmers have argued that N losses in organic farming are much lower than in high-input conventional agriculture, and therefore, they questioned our assumptions used in this study. This, however, has already been considered in the rather conservative loss estimates used in Table 1. Furthermore, when more than approx. 100 kg N ha^{-1} are applied, real 'losses' (L_r), including humification of N, which is not really a loss, are much higher than what had been assumed in these estimates (Figure 4). Both our commercial farm data (Figure 4) and results from a long-term study by CIRAD (2025) in Martinique suggest that L_r is actually higher for organic than for conventional farms. This gap might become smaller after some years as complex organic N fertilisers make N available more slowly (Hirzel et al. 2019), and when higher biological activity combined with higher



Data-pair[1)]	Farm	Sub-set[2)]	Coun-try[3)]	N_f (kg/ha)	Yield (t/ha)	PFP (kg ban./kg N_f)	Resid-ual (r)[4)]	Alert limit[5)]	Thresh-old (t)	Interpre-tation[6)] **e**
73	44	Other	EC	65	58.0	892	2.88	2.5%	1.96	Correct
115	76	Other	EC	28	48.5	1730	2.22	2.5%	1.96	Correct
119	80	Other	EC	18	47.5	2639	2.20	2.5%	1.96	Correct
107	70	Other	DO	19	47.0	2474	2.15	2.5%	1.96	Correct
90	55	Trustw.	CO	96	48.5	507	1.73	5.0%	1.64	False pos.
97	60	Other	DO	128	50.4	393	1.67	5.0%	1.64	Correct
117	78	Other	EC	60	44.4	741	1.60	10.0%	1.28	Correct
86	53	Other	EC	20	39.0	1950	1.36	10.0%	1.28	Correct
125	86	Other	PE	37	40.0	1081	1.34	10.0%	1.28	Correct

FIGURE 5 | (a and b) Banana yield (t ha^{-1}) plotted against N_f (kg N ha^{-1}); (c and d) efficiency of N fertilisation, expressed as PFP in kg ban. kg^{-1} N plotted against N fertilisation. Parts (a and c) show data for all 93 organic farms: trustworthy farms represented by filled circles, other farms by empty circles. The black lines represent the fitted linear model $\eta(N_f) = \beta_0 + \beta_1 N_f$, based on the trustworthy farms (filled circles) only. (b and d) Only 66 'other farms' shown here, but with the same regression lines from (a and c). The red, yellow and green dashed lines represent alert limits of 2.5%, 5% and 10%, respectively. The red triangles symbolise the 2.5% limit only. In (e), we display details of the suspicious cases, using the same colours as in (b) and (d), in decreasing order of the residual. (1) In our dataset, after excluding data from conventional farms, we have 157 data-pairs from 93 organic farms. When we have data from several years or subunits of the same farm, each year or subunit corresponds to one data-pair. (2) We have identified 27 trustworthy and 66 other farms (see Methods). (3)CO, Colombia; DO, Dominican Republic; EC, Ecuador; PE, Peru. (4) Residual (r): see Equation (11); (5) alert limit, linked to the probability of having false positive results, corresponding to the thresholds (t) in the next column. (6) In eight cases the identification of farms as 'suspicious' is likely to be correct and would warrant further investigation. Data-pair 90 is a false positive result. The yield of 48.5 t ha^{-1} using 96 kg N ha^{-1} was obtained on one of the trustworthy farms. This farm has started using leguminous cover-crops, and as BNF in this case is difficult to quantify, we have not considered it here. Assuming, for example, a contribution of 60 kg N ha^{-1} y^{-1} from BNF, the farm would no longer be flagged as 'suspicious'. PFP, partial factor productivity.

SOM levels in organic treatments leads to better N supply from SOM mineralisation. It seems safe to say, however, that on average we cannot expect a ***higher*** PFP from organic fertilisers.

We offer three options for alert limits, linked to the chance for a farm being falsely declared as suspicious (2.5%, 5% and 10%), corresponding to thresholds (t) for the standardised residuals of 1.96, 1.64 and 1.28, respectively. Since such an identification as suspicious is only the first step in the context of the risk analysis that certification bodies must conduct (European Commission 2021), and which should lead to further scrutiny, it may be advisable to use the 10% option. Especially in the range below approx. 100 kg N_f ha^{-1}, most data from the trustworthy farms are below the regression line. Most of the suspicious cases are likely to occur in this range.

We consider our dataset of organic banana farmers to be representative of organic banana production in sofar, as the two major export countries of organic bananas, Ecuador and Dominican Republic (Dawson and Van Der Waal 2023), make up 75% of our farmer sample. It may, however, not be representative in terms of the percentage of fraudulent farmers. We assume that the two certification bodies and the organic farmer association, which provided us with their data, are those which are aware of the problem and try to control it. The individual farms, which provided us with their data, all belong to the trustworthy category. The percentage of fraud may be much higher among the clients of the certification bodies that did not respond to our request.

Generally, $r > t$ does not in itself provide proof of fraudulent behaviour, especially when it occurs only in one year. One may raise the threshold t to reduce the false positive rate, but this comes at the price of an increased false negative rate, that is, fraudulent farms going undetected. The trade-off between false positive and false negative rate deserves further investigation in future. As data on fraudulent cases become available, the statistical modelling may be extended to also comprise a regression curve for fraudulent farms. Such an extended model may then be used to quantify both the false positive and false negative rates and optimise the trade-off between the two. The main challenges in obtaining a curve for fraudulent cases are (1) obtaining reliable data on proven fraudulent cases and (2) dealing with the fact that each fraudulent case involves a different amount of unreported N that also needs to be quantified.

Our statistical approach is in no way restricted to a particular crop. The general framework could easily be applied more broadly. In any application, however, validation will be the key issue. Modelling both the false positive and false negative rates requires further thought if the method is going to be used in any routine application.

5 | Conclusion

Due to excessive variance in Y response to N_f, literature on experimental studies from different countries was not helpful for establishing a reliable benchmark. Detection of suspicious farmers through a simplified N balance was another approach that we considered but did not yield meaningful results either. Case studies from two trustworthy organic farms over 10 years, however, show that there is a close link between N_f and Y. These case studies also show that N supply from SOM mineralisation can act as a short-term buffer, but not as a long-term source of N in organic banana farming.

Finally, we used a subset of 27 trustworthy organic farms to establish a regression of the Y to N_f response. The residual for other farms from this regression line can be used to identify farms with a suspicious Y response. The residual threshold for suspicion can be adjusted on the basis of the sensitivity of the user to false positive and false negative results. This tool provides an efficient method of screening for potential fraud, but conclusions should not be drawn unless the situation persists for more than one year—or other evidence for the use of synthetic fertilisers is found. The equations should be updated as more data from trustworthy farms becomes available.

Our study provides a new proposal for a method to detect fraud in banana production and a first analysis based on a representative dataset to demonstrate the method. Our validation is based on comparing the model alert outputs to known cases of compliance and fraud. We would like to encourage future work that further tests this method and validates it on new datasets. The main challenge in validation will be to obtain independent and accurate verification of fraudulent cases.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.