The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-025-02502-2

LCA FOR AGRICULTURE PRACTICES AND BIOBASED INDUSTRIAL PRODUCTS

Environmental and socio-economic analysis of the Ivorian market vegetables suburban systems in the context of an agroecological transition

Angel Avadí[1,2] · Moussa Dosso[1,3] · Rahim Ouedraogo[4]

Received: 2 May 2024 / Accepted: 10 June 2025

Abstract

Purpose The challenges facing market vegetable production in Côte d'Ivoire, which have resulted in the use of high doses of phytosanitary products and a decrease in soil fertility, have also encouraged the adoption of agroecological practices. The aim of this study is to identify the environmental impacts of market vegetables production systems and determine farmers' motivations for adopting agroecological practices in different production contexts, by means of combined environmental and economic analyses.

Material and methods The environmental analysis was based on LCA of individual technical itineraries (ITKs). Comparisons of ITKs' impact scores, across different groupings and classifications of ITKs, were tested for significance using statistical methods such as ANOVA. Correlation among yield, gross margin, and the phytosanitary use intensity gradient was also tested. The econometric analysis used a multinomial logistic regression to estimate the effect of the different socio-economic factors on Ivorian producers.

Result and discussion For all crops confounded, only the phytosanitary use class was associated with barely significantly different impact scores, while the city of origin was almost significant and seasonality was not significant. Correlations were found between the decision to adopt various practices and explanatory variables such as level of instruction, national origin, age, and gender. Further factors, such as technical and financial support from external actors, may explain farmers' decision to adopt more than six agroecological practices.

Conclusions Environmental impacts of market vegetable crop production in Côte d'Ivoire appear to be determined, to a certain extent, by the intensity of phytosanitary inputs and the geographical location (city). The (self-declared) level of adoption of practices considered as agroecological is not a good predictor of environmental impacts but seems to be correlated with yield. The rationales of adoption of agroecological practices, as well as the associated human health and environmental benefits, should be further explored.

Keywords Market vegetables · Life Cycle Assessment · Agroecological practices · Decision of adoption · Developing and emerging economies

Communicated by Niels Jungbluth.

✉ Angel Avadí
angel.avadi@cirad.fr

[1] CIRAD, UPR Recyclage et Risque, Yamoussoukro, Côte d'Ivoire

[2] Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France

[3] Laboratoire de Biotechnologie Végétale et Microbienne (LBVM), Ecole Supérieure d'Agronomie (ESA),, Institut National Polytechnique Houphouët-Boigny (INP-HB), Yamoussoukro BP 1313 , Côte d'Ivoire

[4] CIRAD, UPR HortSys, Université de Montpellier, Montpellier Cedex 5 F-34398 , France

Published online: 25 June 2025

1 Introduction

1.1 Vegetable production in Côte d'Ivoire: challenges

The current status and challenges of vegetables production in Côte d'Ivoire were recently described in Dosso et al. (2024). The sector has the potential to contribute to multiple Sustainable Development Goals (SDG) (FAO 2023), including but not limited to SDG 2: zero hunger, SDG 8: decent work and economic growth, and SDG 13: climate action, through the implementation of feasible and cost-effective pathways (Malekpour et al. 2023) such as those associated with the agroecological transition.

Vegetable production in Ivory Coast is dominated by small farms that supply the market with diverse produce. This activity generates income for producers and provides them with financial autonomy (Silue 2016; AGRA 2021). The sector meets nonetheless several challenges, including the appearance of diseases and pests, depletion of soil fertility, and limited access to high-quality seeds (de Bon et al. 2019). To protect their crops from pests and diseases, Ivorian producers use high doses of synthetic pesticides, to avoid the risk of losing production. These poor phytosanitary practices are common (Sika 2020; Oula et al. 2021). Moreover, product quality is impacted by the use of unregistered pesticides and not complying with recommended doses (Mambe-Ani et al. 2019).

Moreover, a generalised decrease in soil fertility in the country has been caused by mineral fertilisation and repeated use of soils, combined with reduced fallow durations (Oula 2021). All regions of the country feature low crop yields (de Bon et al. 2019), inclusive in comparison with neighbouring countries (Dosso et al. 2024). Imports reaching 25% offset the difference between supply and demand (AGRA 2021). In urban and suburban (i.e. periurban) areas, agricultural plots are still occupied by renting and squatting, which are the main modes of occupation (Tano et al. 2012; Yeo et al. 2022). These informal agreements do not guarantee the producers land security (Koffi-Didia 2015), which would enable the adoption of more sustainable agricultural practices in the long term. Regarding the levels of technicity, the material used by processors is fairly basic and very few products are actually transformed (Bancal and Tano 2019).

1.2 Complementarity and scale of environmental assessment

As discussed in Dosso et al. (2024), there is growing interest in agroecology as a means of moving towards more sustainable farming and food systems, including in the context of the African and Ivorian market vegetables production (AFSA 2016). However, evidence of the contribution of agroecology to sustainability remains fragmented due to the heterogeneity of methods and data, different scales and timeframes, and gaps in knowledge. A wide variety of frameworks and methods have been developed to assess the sustainability and/or agroecological transition (i.e. the state of progress towards achieving the principles of agroecology) and/or sustainable intensification of farming systems at different scales (Mottet et al. 2020). A general feature across sustainability frameworks is the simultaneous consideration of environmental and socio-economic impacts, as recommended for instance by the widely used Value Chain Analysis for Development (VCA4D) methodology (Fabre et al. 2021), previously applied to African market vegetable value chains (Avadí et al. 2021).

Agroecology implies practices that are often conceived and implemented—or that depend on dynamics—at a "meso" organisational scale, e.g. at the farm scale rather than smaller scales such as the plot or field (e.g. cropping system), or larger scales such as the agricultural region (Dalgaard et al. 2003; Puech et al. 2021; Belmin et al. 2022). For instance, reducing chemical pesticides on a specific crop may depend on other practices such as intercropping and the use of service plants, while partial substitution of synthetic fertilisers may depend on crop rotations, catch crops, and fallows, among other techniques. Some of these practices span several crop cycles, or make sense at the larger farm scale. Nonetheless, the bulk of this work is based on data obtained at the "technical itinerary" level (i.e. the combination of techniques used on an agricultural plot to produce a product given specific constraints; a technical description of an individual distinctive cropping system) rather than at the farm level (i.e. an exploitation managed by the same producer and featuring one or plus technical itineraries), because more often than not Ivorian vegetable producers are actually producers of specific crops, under a monoculture logic (Dosso et al. 2023).

This work focuses on the environmental assessment of the Ivorian market vegetables production in a context of an incipient agroecological transition, complemented by a socio-economic assessment aiming, among other objectives, to understand the rationales for the adoption of agroecological practices. The main goal of this work is thus to identify potential differences in environmental impact intensity explainable by the different strategies adopted by Ivorian market vegetable producers, with a focus on agroecological practices, mostly at the cropping system level, as well as on the drivers for the adoption of said practices.

2 Material and methods

The environmental analysis was based on LCA of individual technical itineraries (ITKs), classified and grouped according to different criteria, namely: season of production (wet vs. dry season), city or origin, type of location (urban, rural, suburban), self-declared system type (conventional vs. transitioning to agroecology), specific crop, dominance of mineral vs. organic fertilisation, and intensity of use of synthetic phytosanitary products (four pseudo-logarithmic classes, to illustrate the intensity of phytosanitary use: 0, ≤ 1, ≤ 10, and > 10 kg active substances/ha). No virtual representative systems (e.g. Avadí et al. 2018) were defined.

Comparisons of ITKs' impact scores, across different groupings and classifications of cropping systems, were tested for significance using basic statistical methods, such as ANOVA. Data on the adoption of different practices considered as agroecological, at the farm level, were combined into a "score of adoption of agroecological practices" and contrasted with impact scores at the same scale (computed as the mean of the different ITKs present per farm, because the original data collection was not exhaustive to all crops per farm), and the correlation between practices and impacts statistically tested for significance. The score of adoption of agroecological practices, despite being computed from ITK data, includes farm-level adoption of certain practices that are conceived at that level, as part of the surveys collected data pertaining the farm. Practices considered as agroecological were as follows: associated animal husbandry, mixed farming, crop associations, crop rotations, concentrated vs. dispersed crop installation, service plants, insect nets or shelters, use of biopesticides, use of organic fertiliser, use of mulching, and fallows: on a scale of 0 (no adoption) to 3 (strong adoption) (Dosso et al. 2024).

The socio-economic implications of strategic choices found to be determinants of significantly different environmental impacts were summarily explored. A detailed socio-economic analysis of the sector is the subject of a follow-up article by our team.

2.1 Data sources and tools

Hundreds of field surveys on operative, social and economic aspects were conducted by the MARIGO project (see Acknowledgements) in the period 2021–2022, representing in excess of 800 individual ITKs and > 400 farms in urban, rural and suburban areas around four Ivorian cities (Abidjan, Yamoussoukro, Bouaké and Korhogo). The resulting dataset (Avadí and Dosso 2023), where data were normalised per hectare, was used to establish a typology of agricultural systems (Dosso et al. 2024) and, in this work, to inform a detailed environmental analysis. The **dataset A**, based on two surveying campaigns, includes inventory and management data as well as economic data featuring operational costs, revenues and gross margins. There was partial overlapping between 2021 and 2022 producers, but each ITK is independent, as the same producer installed different crop systems across years. The data is sufficiently detailed regarding dates and cropping seasons to discriminate individual ITKs.

A third survey was conducted to collect data on farmers' motivations to adopt one or more agroecological practices. Socio-economic data were obtained from 43 farms in the four suburban and urban areas of interest. The producers were selected according to their progress towards agroecology in the first two waves of surveys. Questions on farm characterisation, knowledge of agroecological practices and adoption decisions provided an important source of primary data for further socio-economic analysis, under the form of an additional **dataset B** (Avadí et al. 2024). There are partial overlaps between both datasets. Dataset B was not used in this work but will be used in an upcoming article by our team.

The French Agricultural Research Centre for International Development (CIRAD) LCA research infrastructure (Biard et al. 2011) was used for LCA computations, complemented with ELDAM (Coste et al. 2021), PestLCI (Dijkman et al. 2012) and R (R Core Team 2020). SimaPro, as implemented in the CIRAD LCA research infrastructure, was used for managing life cycle inventories and computing impacts. The Product Environmental Footprint method (Zampori and Pant 2019) was retained as the main method: EF 3.1 (Andreasi Bassi et al. 2023). Certain analyses were conducted on results based on ReCiPe 2016 Endpoint (H) V1.07/World (2010) H/A (Huijbregts et al. 2016).

For background data, ecoinvent processes and elementary flows tailored for Côte d'Ivoire (e.g. water and electricity supply and land use change) were retained.

2.2 Goal and scope

The LCA study had the goal of identifying hotspots in market vegetable production systems, as well as identifying significant differences regarding environmental impacts across different production contexts within Côte d'Ivoire. Notably, find out whether systems labelled as "in transition towards agroecology" by the producers feature different impacts than those labelled as "conventional" The differences between conventional and agroecological systems are thoroughly described in Dosso et al. (2024), and the practices acceptable by agroecology and other strategies towards sustainable agriculture are listed in (Vermeire et al. 2024).

Two functional units were retained: 1 kg of product and 1 ha of product system during one cropping season.

2.3 Building life cycle inventories and interpreting impacts assessment

The dataset of farm survey data was used to construct an inventory file describing all inputs and outputs associated with each ITK, including direct field emissions. The latter were computed using context-optimal models, as recommended in (Basset-Mens et al. 2021), and those emissions associated with pesticide application were modelled with PestLCI, through its online batch computation capabilities (https://pestlciweb.man.dtu.dk/batchcalculation).

Once the inventory file was ready (Supplementary Material), it was used to construct a generic model in SimaPro, which was exported as an Excel file and transformed into an ELDA file with ELDAM. An R script (Supplementary Material) was coded and used to replicate the template ELDA file by updating each instance from the inventory file, where each column represents an individual ITK. The resulting set of ELDA files was reimported into SimaPro to produce ~800 individual processes. The process is depicted in Fig. 1.

As recommended in (Basset-Mens et al. 2021), and despite the technical limitations of most direct field emission models in tropical contexts (Avadí et al. 2022), simple models were retained for N and P emissions (Foster 2005; Prasuhn 2006; Hergoualc'h et al. 2019; Hutchings et al. 2019), namely IPCC 2019 for NO3, N2O, NOx and CO_2 from urea application; EMEP/EEA 2019 for NH3; and RUSLE 2 with SALCA-P for P. The main rationale behind such choice was the sheer number of systems to be modelled and the perceived higher contribution of pesticide emissions to environmental impacts in the Ivorian market vegetable value chain (Dosso et al. 2024).

Regarding pesticide emissions, the conventional assumption that 100% of applied pesticides end up in the soil compartment was replaced by the treatment proposed by the OLCA-Pest project (Nemecek et al. 2022). Under this paradigm, the primary distributions of applied pesticides were computed using PestLCI, in such a way that the mass of applied pesticides was modelled as follows:

- The primary distribution to air ends up in the compartment "air, low population", except for urban agriculture in Abidjan, where it ends up in the compartment "air, high population".
- The primary distributions to soil and crop end up in the compartment "soil, agricultural".

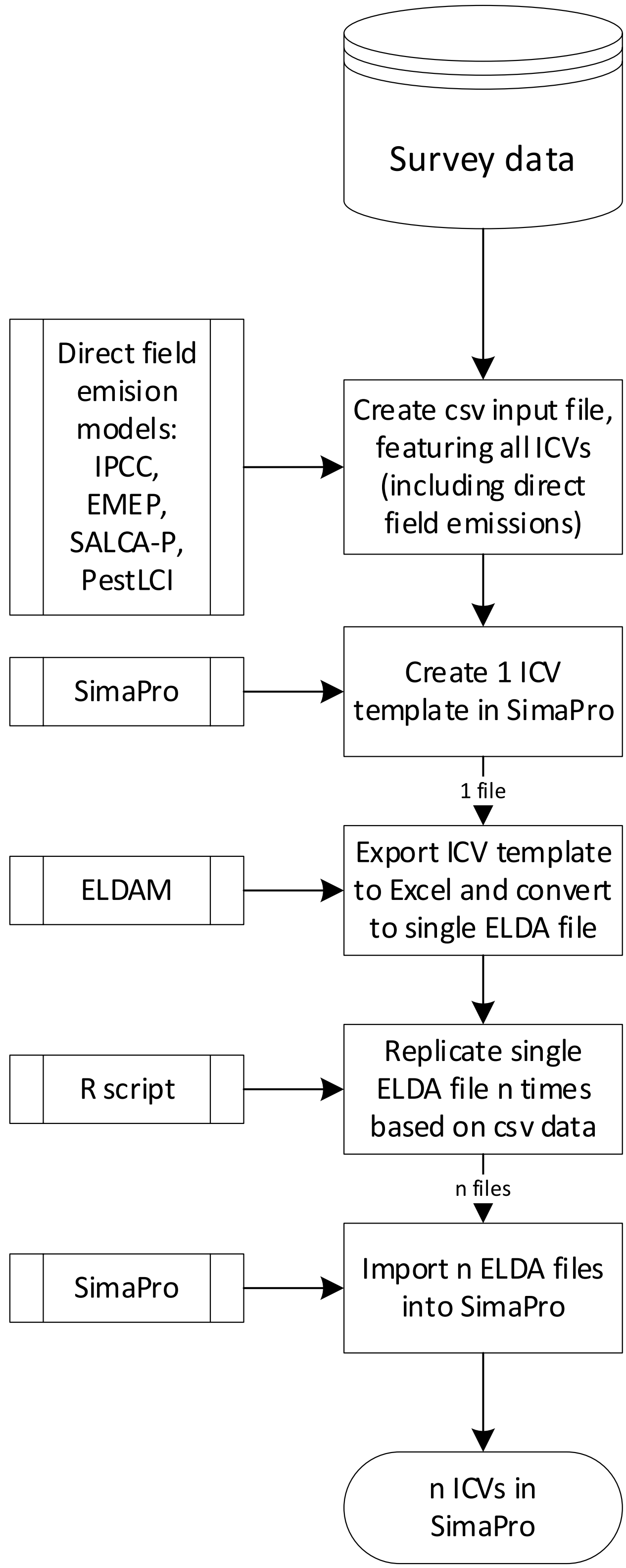


Fig. 1 Data management strategy to generate agricultural LCIs in batch

- The primary distribution to off field ends up in the compartment "water, river" in cases where irrigation is sourced from water surfaces (as irrigation of vegetables is very intensive in Côte d'Ivoire), and in "soil, agricultural" in cases where irrigation is sourced from wells.

Impacts were computed by means of the EF 3.1, in terms of both midpoints and damage indicators (single score). Data uncertainty, including that due to natural variability, was integrated by computing individual ITK impacts, and retaining central tendency statistics such as means and medians.

2.4 Socio-economic analyses

In addition to an economic analysis based on farm accounts to compare conventional and agroecological practices, we are interested in the various factors (economic and social) that may hinder the adoption of agroecological practices. Explanations were sought regarding the intensive and systemic use of phytosanitary, through the accounts-based analysis and an econometric analysis.

The accounts-based economic analysis was based on statistical analysis with Spearman's correlation coefficient, to verify correlation among yield, gross margin and the phytosanitary use intensity gradient. The correlation analysis was carried out using R version 4.3.0. Gross margins were computed as the difference between total sales and total expenses, including amortisation of capital goods.

The econometric analysis used a multinomial logistic regression to estimate the effect of the different socio-economic factors on Ivorian market vegetable producers (Greene et al. 2011; Bourbonnais 2021).

Let Y^* be a continuous latent variable measuring the different level of adoption of agroecological practices (Eq. 1):

$$y_i^* = \theta_0 + \theta_1 x_{1i} + \cdots + \theta_k x_{ki} + e_i = e_i' \theta + e_i \tag{1}$$

where y_i^* is the latent variable for individual i, $x_1 \ldots x_k$ are the explanatory variables with coefficients θ that influence y_i^* and e_i is the error term. The decision model is based on the different values (V) of y_i^* corresponding to the intervals or different threshold parameters $C_1 \ldots C_v$ determining y_i^* (Eq. 2).

$$y_i^* = \begin{cases} 0 \; if \; y_i^* \leq C_1 \\ 1 \; if \; C_1 < y_i^* \leq C_2 \ldots \\ V \; if \; C_v < y_i^* \end{cases} \tag{2}$$

Let P_i be the probability of occurrence of each event for individual i (Eq. 3):

$$\begin{gathered} P_{i0} = Prob(y_i = 0) = Prob(x_i'\theta + e_i < C_1) = F(C_1 - x_i'\theta) \\ P_{i1} = Prob(y_i = 1) = Prob(C_1 < x_i'\theta + e_i \leq c_2) = F(C_2 - x_i'\theta) - F(C_1 - x_i'\theta) \ldots \\ P_{i1} = Prob(y_i = 1) = Prob(x_i'\theta + e_i < C_v) = 1 - F(C_v - x_i'\theta) \end{gathered} \tag{3}$$

The coefficients θ of the model are estimated by maximum likelihood, with F the function of distribution of the normal or logistic probability distribution is (Eq. 4).

$$F(t) = \frac{e^t}{1 + e^t} \; and \; \sum_{i=0}^{V} P_i = 1 \tag{4}$$

The different explanatory variables x are the age of the farmer (age), the gender of the farmer (gender), the number of family members (family); the number of adults in the family (adultes); the level of instruction (instruc: Unschooled = 1, Primary school = 2, High school = 3, University = 4), membership of an organisation of farmers (organiza), being autochthone or not (origin), being located in urban, suburban or not (location), property right (property), level of income (income), the area of the farm (area), and the impact of chemicals on human health and the environment (singlescore).

3 Results and discussion

3.1 Inventory analysis

Based on dataset A, the resulting life cycle inventories were classified and summarised following various criteria and statistics, to extract a priori hints on potential differences across cities, location types, crops, seasons, etc. Disaggregation by geography (Table S1) and crop (Table S2) suggest certain apparent differences in yields and input intensities. The input intensity (synthetic fertilisers and phytosanitary products) varies significantly (one-way ANOVA, p-value < 0.05) across crops, with "European" (i.e. non-West African and imported cultivars (Bancal and Tano 2019)) crops among the top 5 crops receiving the highest amounts of synthetic inputs (Table 1).

Table 1 Selected crops (all origins confounded) ranked by ascending input intensity (according to median values)

Crops	Medians (kg/ha)		Means (kg/ha)	
	Mineral fertilisers	Pesticides	Mineral fertilisers	Pesticides
Spring onions*	77	3.3	242	12.0
Lettuce*	122	1.3	406	7.0
Okra	155	0.4	347	2.3
Eggplant (African)	167	2.2	387	8.0
Onion	214	0.4	502	1.8
Chili pepper	226	0.3	449	1.6
Tomato	229	0.4	436	2.8
Green beans*	298	0.3	414	2.1
All crops	318	0.5	503	4.2
Bell paper*	354	1.0	354	1.0
Eggplant (European)*	443	0.6	629	1.8
Cucumber*	465	0.5	675	4.6
Zucchini*	528	0.6	696	2.7
Cabbage*	545	0.5	657	2.6
Carrot*	575	0.1	650	1.4

* "European" vegetables

In Korhogo, the main source of water for domestic and agricultural needs is wells (Yapo et al. 2016). Watering crops is manual by means of cheap watering cans (Coulibaly 2017), which limits the water supply to crops.

Market gardening is heavily practised by non-nationals in the urban areas of Yamoussoukro and Bouaké. These producers occupy the land by squatting despite urban pressure (Tano et al. 2012; Kra 2018). The most commonly used areas are low-lying ones, the banks of urban lakes and other areas declared unsuitable for building. These individuals have no access to land beyond squatting or short-term renting and therefore have difficulty finding good, free, irrigable land. The lack of land means that they grow a lot of leafy vegetables (lettuce, cabbage, spring onions, African leafy vegetables), which allows them to make the best use of the land (de Bon et al. 2019).

Market gardening is mainly performed by women in Korhogo (Traoré 2022). Difficult access to land has enabled them to organise themselves and buy land in groups. By dividing and subdividing the land, each woman can have a portion on which to produce. Customary laws are not favourable to land acquisition (Akpa 2022).

At the farm level, the analysis of the variable score of adoption of agroecological practices showed that most producers adopted at least one practice, with 20% of them (all cities confounded) featuring a score higher than the mean (8.4 $\pm$4.5) or the median (8.0) score. Abidjan features the lowest mean score (6.9) and Korhogo the highest (10.5), out of a maximum possible score of 34, representing the optimal adoption of all retained agroecological practices. The adoption of practices seems to follow a lognormal distribution (Supplementary Material), typical of industrial and agricultural efficiency metrics, including LCA data, as well as of natural phenomena (Limpert et al. 2001; Diwakar 2017; Andersson 2021; Heijungs 2023). Moreover, from a sample of 274 producers in dataset A, 79% of them consider vegetable production as their main economic activity, 36% of whom perform another income-generating activity.

3.2 Impacts analysis and interpretation

Crop systems, including their associated impact assessment results, were classified and summarised following various criteria and statistics. The classification criteria were season of production, city or origin, type of location (urban, rural, suburban), self-declared system type (conventional vs. transitioning to agroecology), specific crop, dominance of mineral vs. organic fertilisation, and intensity of use of synthetic phytosanitary products (four pseudo-logarithmic classes: 0, ≤ 1, ≤ 10, and > 10).

The choice of central tendency statistics (means, medians) is non-trivial, as the distribution of impact scores is log-normal (not shown) (Fig. 2) and features a very large variability (Fig. 3). To retain more conservative (i.e. higher) impact scores, we used mainly means, except in specific cases when we contrasted means and medians.

There are apparent differences across individual crops and the above-described groupings of impact scores, including when impacts are disaggregated into individual impact categories (Fig. 4).

Some of the apparent differences are dramatic, such as impacts per crop $\times$ season of production and crop x city of origin (Fig. 5).

These apparent differences in impacts across types, according to these classifications, were statistically tested to determine whether they were significant, by testing the correlations of various operational characteristics with impact scores to identify significant potential differences, leading to further investigation of these factors. Factors of interest were: season of production, city or origin, type of location, self-declared systems type, specific crop, dominance of mineral vs. organic fertilisation, and intensity of use of synthetic phytosanitary products. For all crops confounded, only the phytosanitary use class was found to be associated with barely significantly different impact scores (one-way ANOVA, p-value $=0.049$), while the city of origin was almost significant (one-way ANOVA, p-value $=0.051$). Against all odds, as according to local experts and literature (e.g. Abang et al. 2014; Kone et al. 2017), most pests and diseases are generally more prevalent in the region during the rainy season; seasonality did not contribute significantly to differences in impacts.

Moreover, when total phytosanitary inputs are contrasted with associated ITK yield, there is no correlation,

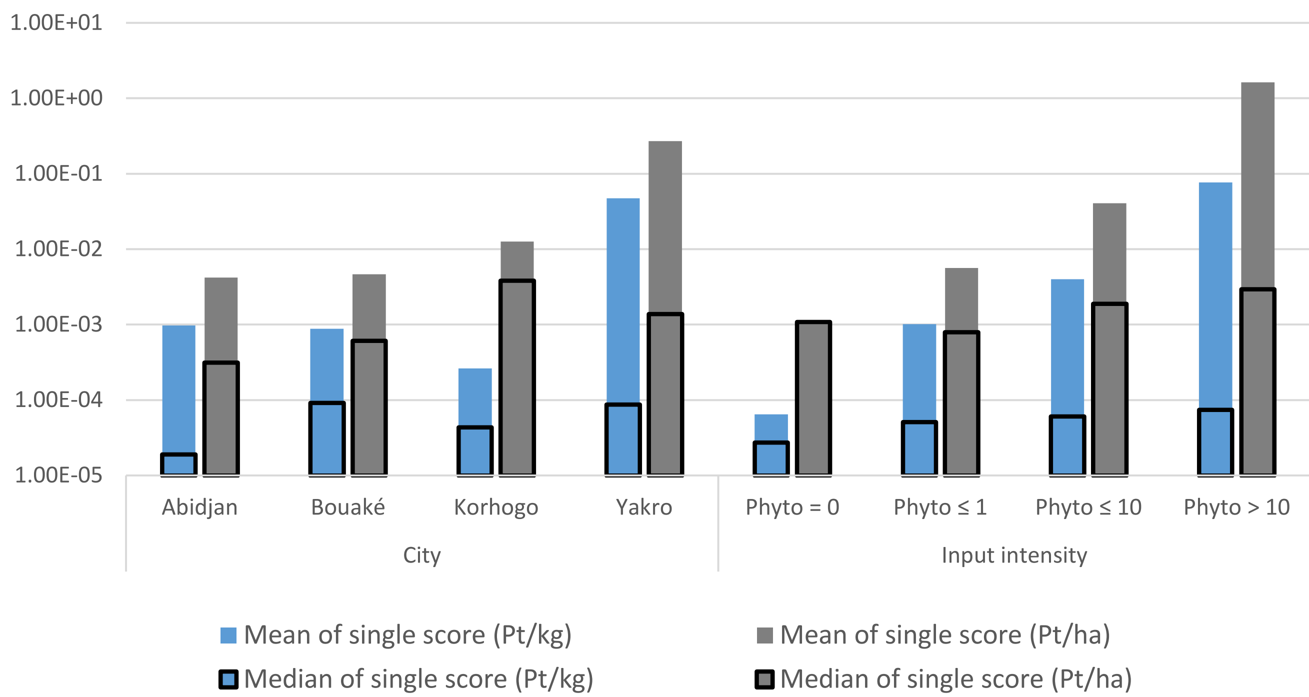


Fig. 2 Environmental impact score (EF 3.1, single score) of all crops confounded per city of origin and phytosanitary input intensity; per kg of product and per ha of crop, based on mean and median values

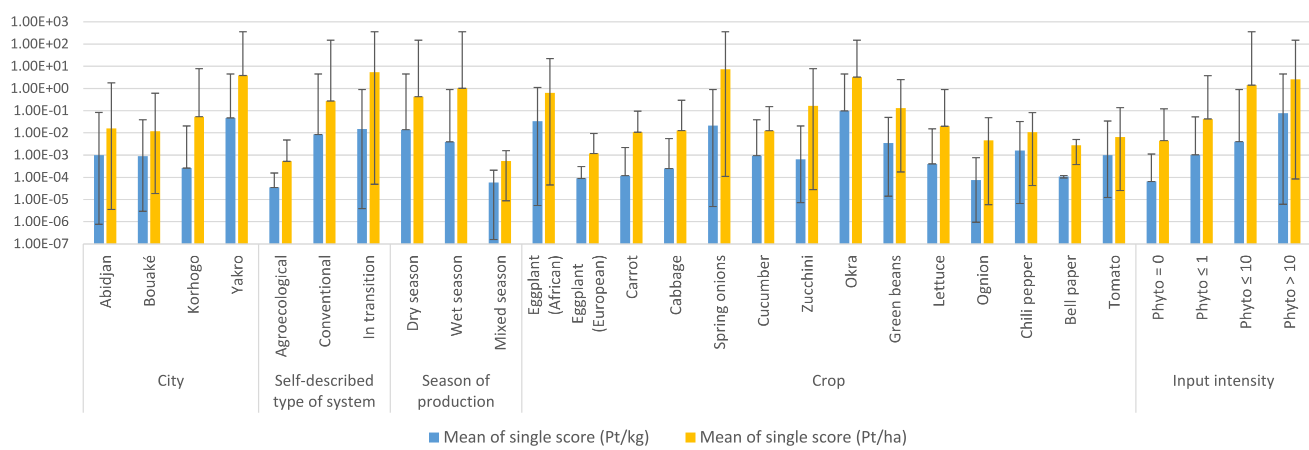


Fig. 3 Environmental impact score (EF 3.1, single score) of all crops confounded and aggregated by different criteria, as well as per individual crop; per kg of product and per ha of crop, based on mean values (error bars represent the range of observed values)

and furthermore the corresponding mean impacts per city do neither correlate with the phytosanitary/yield pair, be it using means or medians (Fig. 6).

The self-declared system type (conventional vs. agroecological or in transition to agroecology) is associated with significantly different impact scores per ha at the farm level (one-way ANOVA, p-value $=0.02$), but not at the technical itinerary level. On the other hand, no significant correlation was found between the self-declared system type and the score of adoption of agroecological practices (one-way ANOVA, p-value >0.05). These results suggest, among other possible explanations, that producers do not have a clear idea of what agroecology entails, or that efforts towards an agroecological transition are not systematic (for instance, certain technical itineraries within a farm feature agroecological practices while others do not, and only certain farm level practices are adopted). These and other hypotheses will be further tested.

A more detailed exploration of the contribution to impacts by city (Table 2), which despite not implying

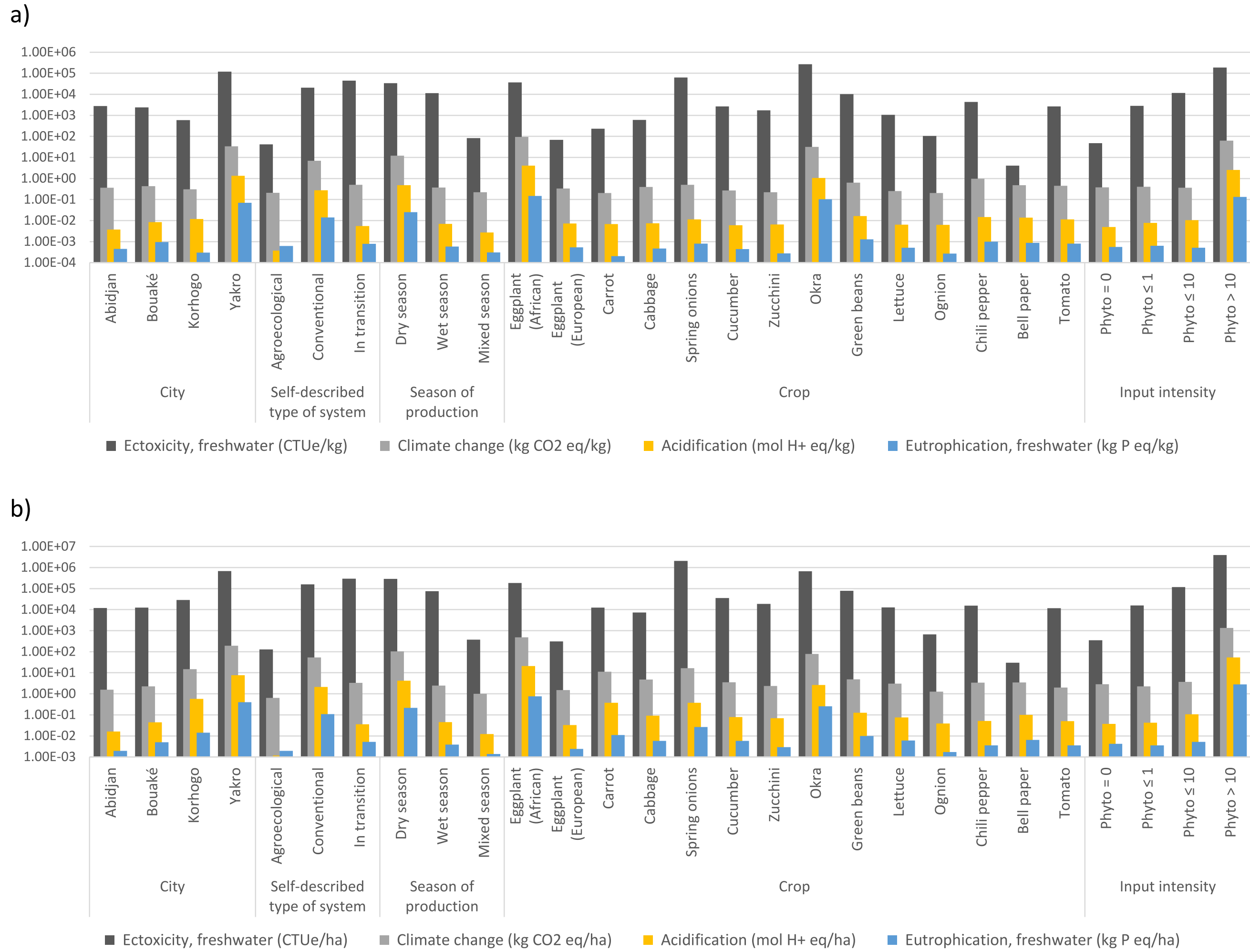


Fig. 4 Environmental impact scores (EF 3.1, selected impact categories, midpoints) of all crops confounded and aggregated by different criteria, as well as per individual crop; per (**a**) kg of product and (**b**) per ha of production, based on mean values

significant differences across impacts remains a key decision-making criterion, shows that median impacts (single score, selected impact categories) are the highest in Bouaké, probably due to the yields being the lowest amongst cities. For acidification in particular, the highest median impacts take place in Korhogo, probably correlated with the higher intensity of synthetic fertilisers' use. Despite Yamoussoukro featuring much larger pesticide inputs than the other cities, their impact is not reflected in higher median ecotoxicity. The much higher values of mean impacts are due to a few extremely input-intensive systems.

A more detailed exploration of the phytosanitary use class, disaggregating the data per crop, identified that only in the cases of cabbage, zucchini and okra were the differences amongst impacts significant (one-way ANOVA, p-value < 0.05). Overall, across crops, it was not observed a systematic increase in impacts per ha of production associated with increasing phytosanitary use intensity (Fig. 7a). The differences in impacts amongst cities of origin are significant (one-way ANOVA, p-value < 0.05) only for all crops confounded and for a handful of individual crops, namely European eggplant, green beans and tomato (Fig. 7b). Mean single scores per kg of product are lowest for Korhogo, but median ones are lowest for Abidjan (Table 2).

A contribution analysis on two contrasted ITKs (Table 3) shows that the main contributors to impacts are, systematically, fertiliser provision and use, through direct field emissions. The contribution of pesticides (notably their provision) is proportional in order of magnitude to the phytosanitary use intensity.

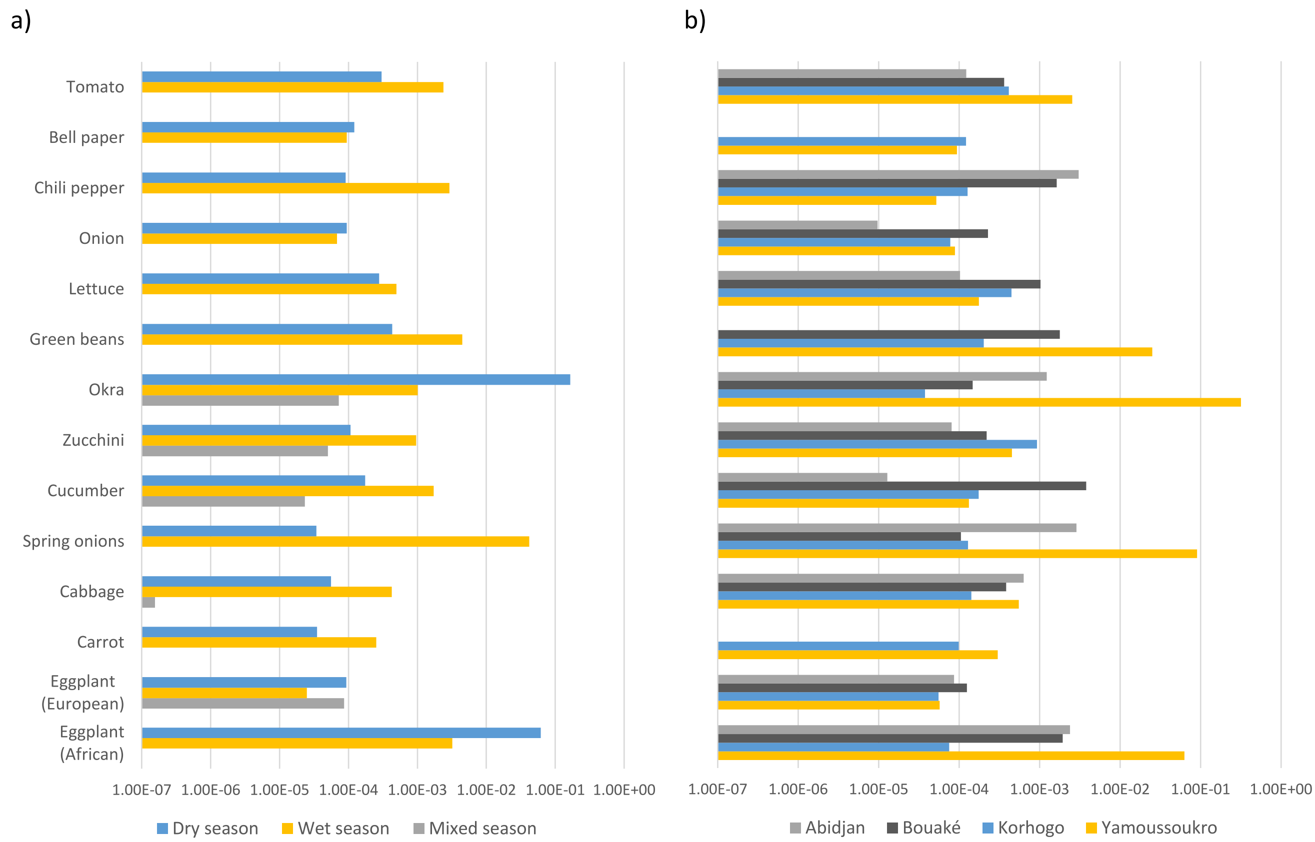


Fig. 5 Apparent differences in environmental impact score (EF 3.1, single score), per selected crops and per (**a**) season and (**b**) city of origin; per kg of product, based on mean values

Regarding the score of adoption of agroecological practices vs. impacts at the farm level (Fig. 8a), no correlation was found between the medians of the two variables (despite significantly different impacts per score of agroecological practices), and no regression model was able to link them with an $R^2 > 0.1$. Moreover, no correlation was found between yield and environmental impact, despite a reasonably good model ($R^2 = 0.88$) linking median yields to median scores of agroecological practices (Fig. 8b). When all individual impact scores per farm are classified by score of adoption of agroecological practices—excluding the few (8) farms which did not declare adopting any agroecological practice—only a weak (positive and not the expected negative) correlation between impacts and scores was found (Fig. 9). These results suggest that, despite impact scores being significantly different across scores of adoption of agroecological practices (one-way ANOVA, p-value < 0.05), the level of adoption of practices considered as agroecological is not a good predictor of environmental impacts. In contrast, a recent study conducted in Benin comparing conventional and organic vegetables production found significant differences in environmental scores across production types, with the larger impact associated with organic production (Avadí et al. 2021).

3.3 Preliminary socio-economic implications of phytosanitary use intensity and agroecological practices adoption

The results of the environmental impact analysis suggest the need for a socio-economic analysis to better characterise the impacts of the varying levels of adoption of agroecological practices. This characterisation enables a better understanding of farmers' choices in a sustainability dynamic in the agroecological transition process. For instance, the variable "city or origin" is significant in terms of environmental impact. This means that there is a difference in behaviour depending on the location of farmers. This is mainly linked to consumers' choices,

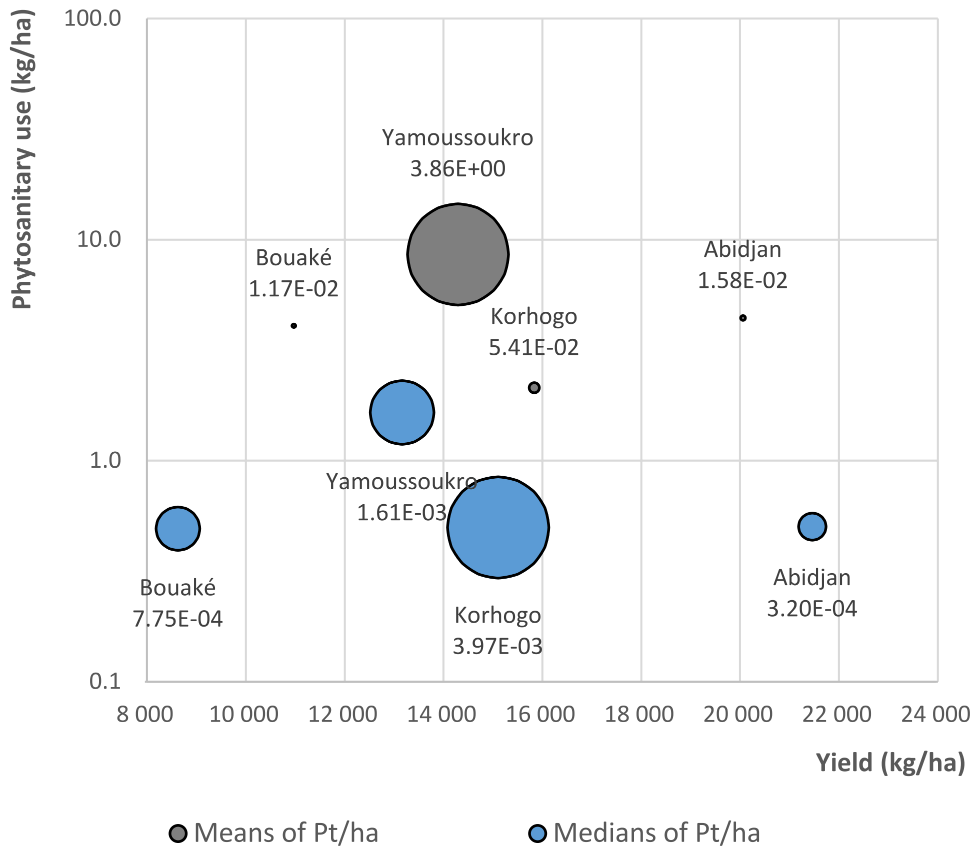


Fig. 6 Relations at the technical itinerary level among mean phytosanitary use and yield, per city, with bubble sizes representing environmental impact score per ha (EF 3.1, single score)

which can influence the supply of products derived from agroecological practices. (Ouedraogo et al. 2024a) shows that consumers in Abidjan have a lower willingness to pay for organic vegetables than those in Yamoussoukro or Bouaké.

Furthermore, the relationship between agroecological practices and environmental impact appears to be not significant for farmers. This calls for a better understanding of farmers' social representation of agroecology.

The results of the correlation test, based on dataset A, indicate that the correlation among yield, gross margin and phytosanitary use intensity (in terms of individual product types), all variables normalised per ha, is weak (Fig. 10). Phytosanitary management is not the main key to explain the difference in gross margin between the different farms and ITKs. The price of vegetables at the local market could influence gross margins; moreover, there is a fluctuation in prices throughout the year that the producer cannot influence (Kouame et al. 2017; Dosso et al. 2023). Gross margins per farm do not seem to correlate with the adoption of agroecological practices nor with environmental impacts (Fig. 11).

Table 2 Mean impacts and key operational features of all systems (technical itineraries) confounded and aggregated by city of origin, based on medians and means

City	Statistic	Acidification	Climate change	Ecotoxicity, freshwater - organics	Eutrophication, freshwater	Single score		Yield	Area	Pesticides (synthetic)	Nutrients (N + P + K)
		mol H+ eq/kg	kg CO2 eq/kg	CTUe/kg	kg P eq/kg	Pt/kg	Pt/ha	kg/ha	ha	kg/ha	kg/ha
Abidjan	Medians	1.79E-03	0.11	2.65	2.32E-04	1.90E-05	3.20E-04	21 504	0.06	0.5	91
	Means	3.76E-03	0.37	2 773	4.56E-04	9.76E-04	1.58E-02	20 058	0.23	4.4	237
Bouaké	Medians	5.09E-03	0.26	30.46	5.57E-04	9.18E-05	7.75E-04	8 667	0.15	0.5	275
	Means	8.50E-03	0.43	2 390	9.58E-04	8.83E-04	1.17E-02	10 970	0.19	4.1	477
Korhogo	Medians	6.70E-03	0.19	5.81	1.63E-04	4.34E-05	3.97E-03	15 145	0.01	0.5	686
	Means	1.19E-02	0.31	600	2.99E-04	2.63E-04	5.41E-02	15 834	0.02	2.1	744
Yamoussoukro	Medians	2.36E-03	0.18	27.27	3.36E-04	8.73E-05	1.61E-03	13 205	0.06	1.7	98
	Means	1.35E+00	33.84	119 302	7.04E-02	4.75E-02	3.86E+00	14 293	0.18	8.6	372

The highest values for each criteria are highlighted in grey for medians and in light blue for means

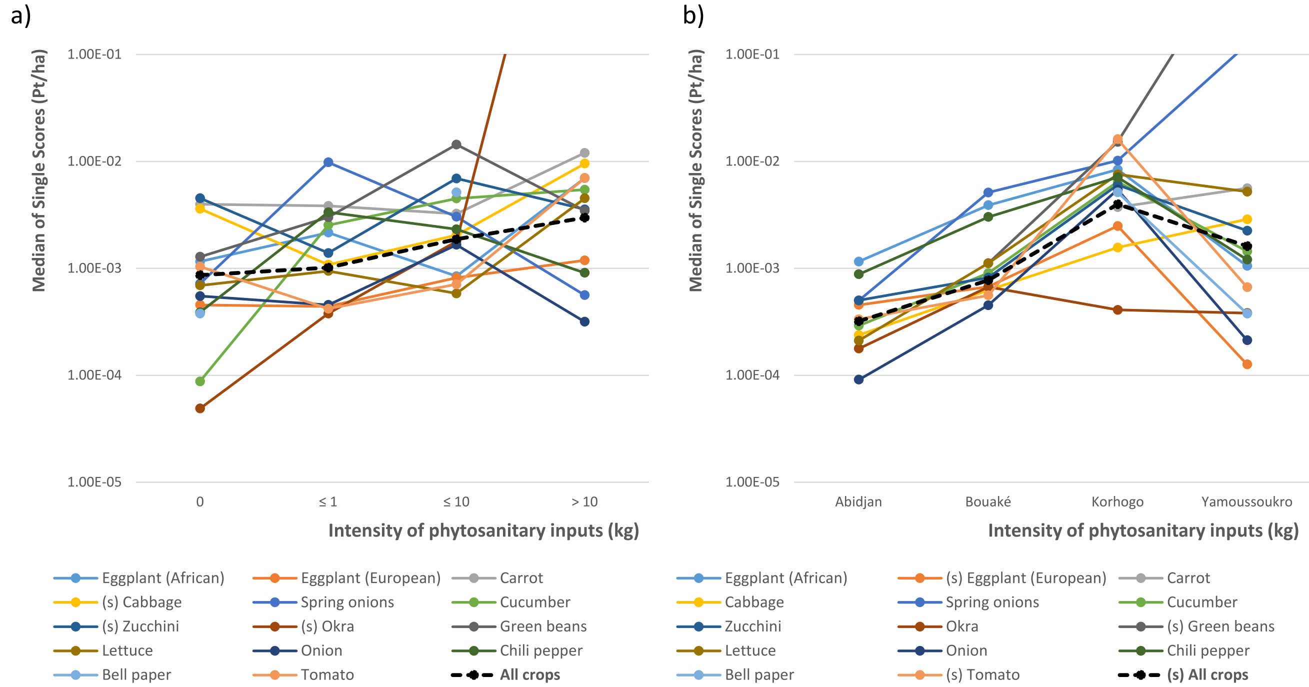


Fig. 7 Relation between (**a**) phytosanitary use intensity and (**b**) city of origin vs. environmental impact score (EF 3.1, single score per ha) for some key market vegetable products in Côte d'Ivoire; based on median values. "(s)" identifies significant differences across impact scores

The level of adoption of agroecological practices refers to the adoption of crop association, crop rotation, biopesticides, service plants, net shelters, organic fertilisation, mulching straw, fallows and number of ITKs; practices were observed in the studied zones (Martin et al. 2006; Drabo et al. 2022; Dosso et al. 2023). The study was based on 431 farmers, having adopted between one and seven agroecological practices out of nine (dataset A). Thus, the dependent variable is polychotomous, as it is based on more than two possible answers. This score of adoption (laep) is not the same used until now, as it does not include intensity of adoption, but instead adoption as a binary (i.e. categorical yes/no) choice.

Table 3 Contribution analysis of two example technical itineraries featuring different phytosanitary use intensities; per production cycle

	A-AER-01-Cib Spring onion	Y-BAL-05-Aub African eggplant
Phytosanitary use intensity class	≤ 1	> 10
Fertilisers (provision)	22.3%	30.3%
Fertilisers (direct field emissions)	56.0%	29.3%
Pesticides (provision)	0.8%	16.0%
Pesticides (direct field emissions)	0.8%	0.3%
LULUC + water use	17.6%	3.0%
Fuel		15.9%
Other inputs	2.6%	5.2%

Percentages represent relative contribution to the ReCiPe single score

Among the nine main agroecological practices, the distribution of the dependent variable shows that all the farmers adopted at least one practice. Only 0.01% of farmers adopted 7 practices (which is the maximum of observed adoption), 3% adopted 6, 13% adopted 5, 27% adopted 4, 50% adopted 3 and 73% adopted 2.

Two variables were significant in explaining the decision of farmers to adopt two types of agroecological practices. A positive correlation was found between the level of adoption of agroecological practice (laep) and the variables instruction (instruc) and origin (Supplementary Material). Indeed, if the level of instruction of farmers increases by one unit, their laep increases by 0.064. And native farmers' laep is 0.077 more than the others (Supplementary Material). There is a positive correlation between the decision of farmers to adopt three agroecological practices and their level of income, whereas a negative correlation was found between this laep and the variable "gender". If the farmers' income increases by one unit, their laep increases by $7.65E-08$. However, the laep of men is 0.123 more than that of women.

Three variables were significant when the laep is 4: a positive correlation was found between laep and age and income and a negative correlation between laep and the variable gender. Older famers are more likely to adopt agroecological practices. If the farmers have one more year, their leap increases by 0.0023. If the farmers' income increases by one unit, their laep increases by $2.59E-08$. However, being women improve the adoption of agroecological practices by 0.57 compare to men.

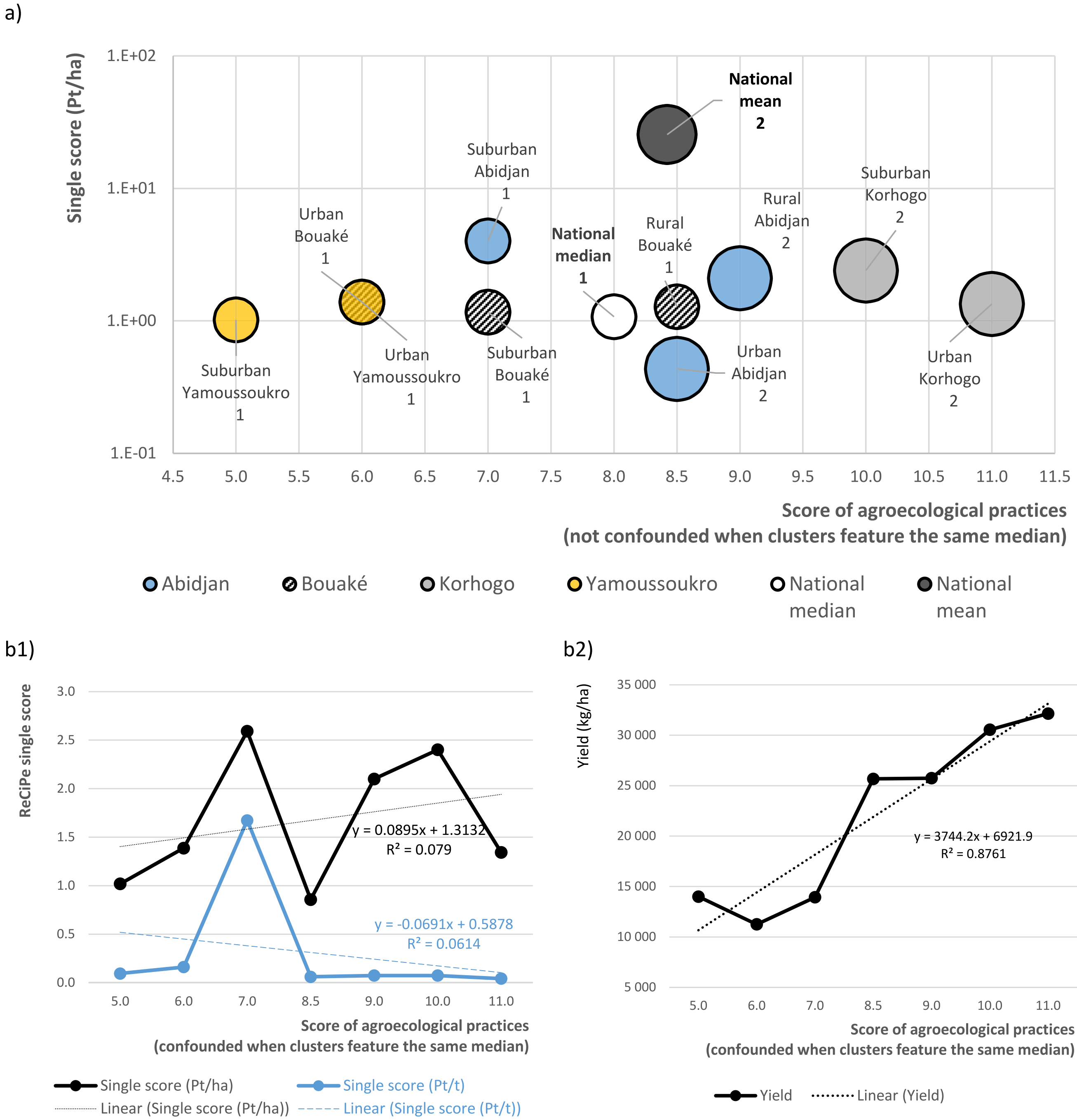


Fig. 8 Relations at the farm level, where farms are aggregated as "clusters" per city of origin and type of location, and all variables are shown as median values: **a** scores of adoption of agroecological practices vs. environmental impacts per ha, with number of technical itineraries per farm as labelled bubble size; **b1** scores of adoption of agroecological practices vs. environmental impacts per ha and per t and **b2** scores of adoption of agroecological practices vs. farm yield

Two variables were significant when the laep is 5: laep was positively correlated with the variables age and origin. Older farmers are 0.0025 more able to adopt than younger. Those who adopt at less than 5 agroecological practices are native, and this impacts their decision by 0.0496. Two variables were also significant when the laep is 6: There are a positive correlation between laep and income and a negative correlation between laep and location. The income is important when farmers adopt at less than 6 agroecological practices, and when the farmers' income increases by one unit, their decision to adopt increases by 5.12E-09. However, when the laep is 7, the different variables identified

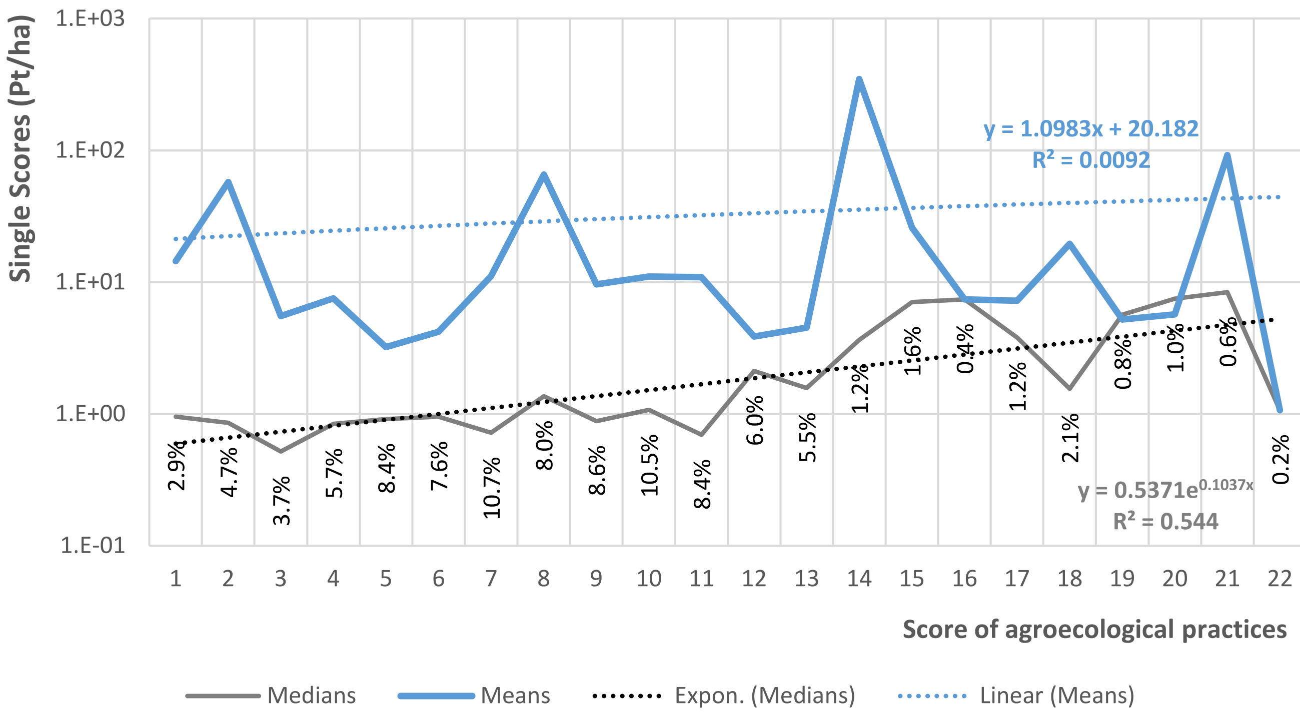


Fig. 9 Relations at the farm level between scores of adoption of agroecological practices and environmental impacts per ha (medians and means). Percentages represent the proportion of farms featuring each score

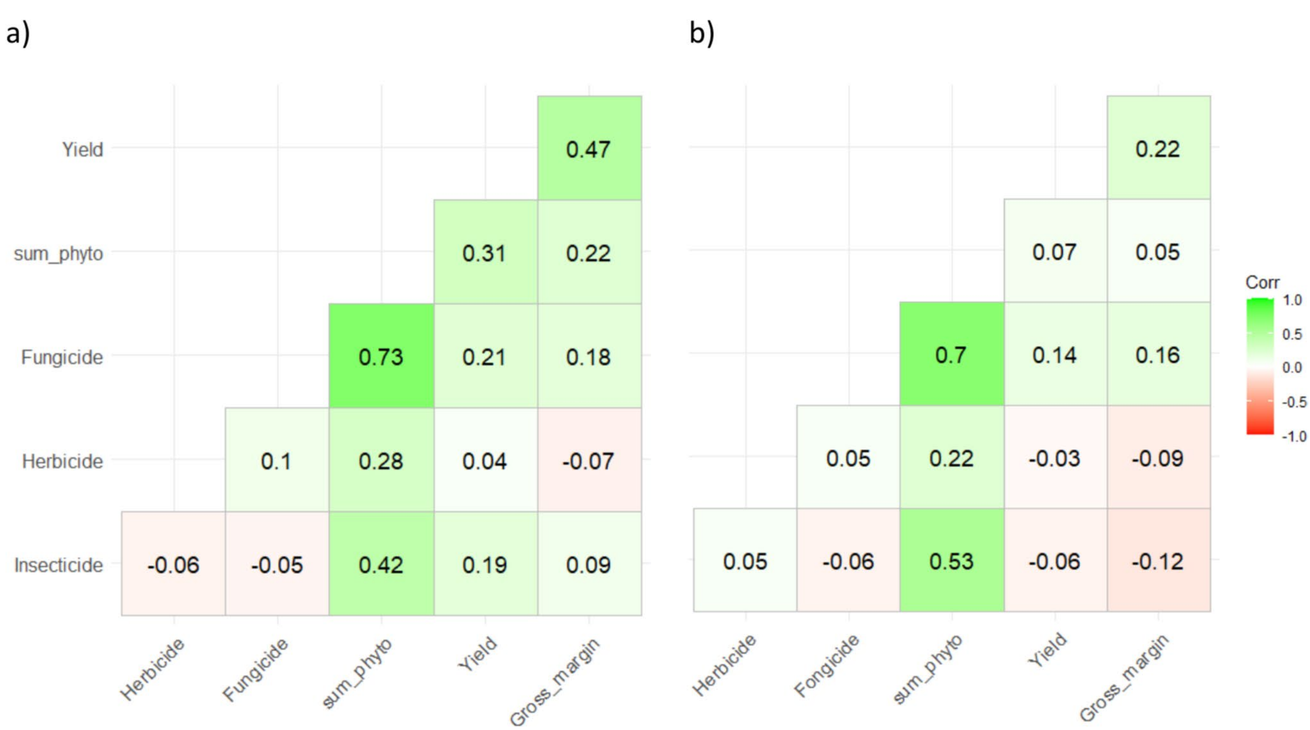
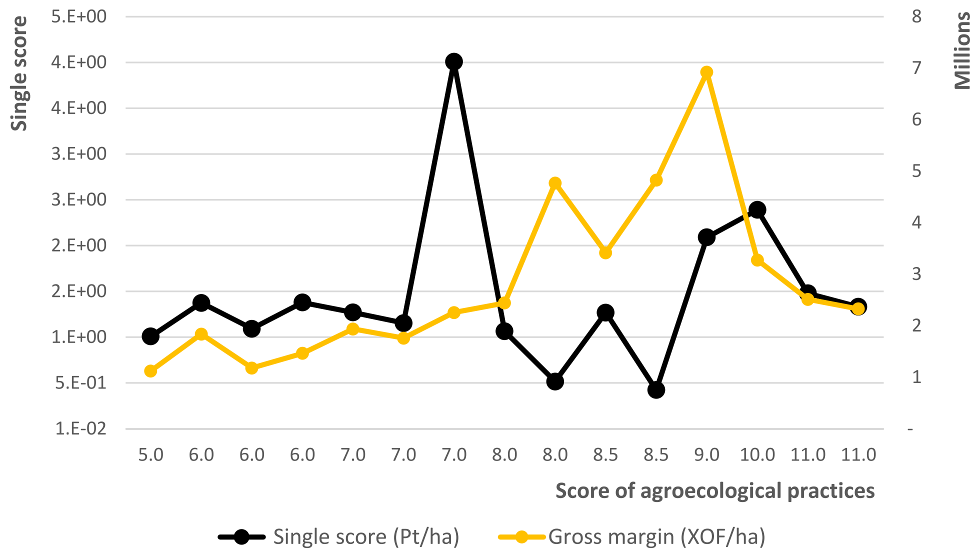


Fig. 10 Spearman's correlation coefficient matrix of inputs vs. yields vs. gross margins, **a** per farm and(**b**) per ITK. "sum_phyto" refers to the sum of masses of all phytosanitary inputs, in terms of active substances. All variables are expressed in kg/ha

Fig. 11 Relations at the farm level between scores of adoption of agroecological practices and environmental impacts per ha and gross margins per ha; medians per city of origin and type of location



are not significant. It means that there are other factors that may explain farmers' decision to adopt more than 6 agroecological practices. These factors likely include technical and financial support from external actors, such as NGOs (Ouedraogo et al. 2024b).

3.4 Limitations and directions for further research

The main limitation of this study pertains to the level of detail/granularity of the analyses, as general national and regional trends were addressed, without investigating, for instance, crop-specific dynamics. Moreover, as phytosanitary products use is a main driver for impacts, a more detailed analysis of its dynamics is necessary to better understand the drivers for current practices (e.g. in terms of product selection, number of applications and amounts applied per cycle in contrast with agronomic guidelines, and rationale for application). A separate study on the phytosanitary issues is currently being carried out by our team.

The rationales of vegetable producers adopting agroecological practices, as well as the associated benefits on human health, environmental and wellbeing, should be explored using additional complementary approaches, such as hidden costs or negative externalities of chemicals. Moreover, the study of adoption of agroecological practices from the point of view of innovation theory (Faure et al. 2018), would be highly informative, and perhaps extrapolable to the region, as there is an important transnational movement of people in West Africa in the context of agriculture (Hollinger and Staatz 2015), now exacerbated by climate change (IOM 2020). A separate study on adoption is currently being carried out by our team.[1]

[1] All publications associated with the MARIGO project will be listed on the MARIGO project's website: https://www.projet-marigo.org/la-communication-du-projet/produits-com

4 Conclusions

Environmental impacts of market vegetable crop production in Côte d'Ivoire are determined, to a certain extent, by the intensity of phytosanitary inputs and the geographical location (city), with Bouaké and Yamoussoukro featuring the highest impacts by all metrics, depending on the choice of statistics (medians or means, respectively). Korhogo features the highest rates of pesticide use amongst the four cities, across statistics. European crops receive significantly higher inputs than African ones, and thus, some efforts must be made to encourage farmers to reduce chemicals use overall and to privilege (market demand-permitting) better adapted native crops. This will help to improve people's and ecosystems' health.

The (declared) level of adoption of practices considered as agroecological is not a good predictor of environmental impacts but seems to be correlated with yield. Complex socio-economic and institutional dynamics underscore the adoption of agroecological practices. These include intrinsic characteristics of farmers, as well as their social capital.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-025-02502-2.

Acknowledgements The authors acknowledge the following collaborators: MARIGO WP leaders, PhD students, interns and other students participating in field surveys and project deliverables.

Funding Open access funding provided by CIRAD. This work has been financed by the MARAÎCHAGE AGROÉCOLOGIQUE PÉRI-URBAIN–DeSIRA MARIGO project (https://www.projet-marigo.org/), 2021–2025 (grant number FOOD/2020/419–988).

DeSIRA: Development Smart Innovation through Research in Agriculture,FOOD/2020/419-988

Data availability The authors confirm that the data supporting the findings of this study are either available within the article and its Supplementary Material, or available for download from the Cirad Dataverse (https://doi.org/https://doi.org/10.18167/DVN1/FFV3W6 and https://doi.org/https://doi.org/10.18167/DVN1/HG0DNY).

Declarations

Competing interest The authors declare no competing interests.

References

Abang AF, Kouamé CM, Abang M et al (2014) Assessing vegetable farmer knowledge of diseases and insect pests of vegetable and management practices under tropical conditions. Int J Veg Sci 20:240–253. https://doi.org/10.1080/19315260.2013.800625

AFSA (2016) Agroecology: the bold future of farming in Africa. AFSA & TOAM. Dar es Salaam. Tanzania

AGRA (2021) Food market demand & competitiveness. West Africa Region Report. Alliance for a Green Revolution in Africa (AGRA). Nairobi, Kenya

Akpa L G (2022) Dynamiques d'accès à la terre des femmes maraichères en milieux urbains et périurbains de Korhogo au nord de la Côte d'Ivoire. (Unpublished master's thesis). Université de Liège, Liège, Belgique. https://matheo.uliege.be/handle/2268.2/16345

Andersson A (2021) Mechanisms for log normal concentration distributions in the environment. Sci Rep 11:1–7. https://doi.org/10.1038/s41598-021-96010-6

Andreasi Bassi S, Biganzoli F, Ferrara N, Amadei A, Valente A, Sala S, Ardente F (2023) Updated characterisation and normalisation factors for the environmental footprint 3.1 method. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/798894

Avadí A, Corson MS, van der Werf HMG (2018) Modelling environmental effects of selected agricultural management strategies with regional statistically based screening LCA. Int J Life Cycle Assess 23:12–15. https://doi.org/10.1007/s11367-017-1300-4

Avadí A, Hodomihou NR, Amadji GL, Feder F (2021) LCA and nutritional assessment of southern Benin market vegetable gardening across the production continuum. Int J Life Cycle Assess 26:1977–1997. https://doi.org/10.1007/s11367-021-01977-z

Avadí A, Galland V, Versini A, Bockstaller C (2022) Suitability of operational N direct field emissions models to represent contrasting agricultural situations in agricultural LCA: review and prospectus. Sci Total Environ 802:149960. https://doi.org/10.1016/j.scitotenv.2021.149960

Avadí A, Dosso M (2023) Données opératives issus des enquêtes auprès des producteurs maraîchers urbains et périurbains de la Côte d'Ivoire, 2022. Yamoussoukro, CIRAD Dataverse, V2. https://doi.org/10.18167/DVN1/FFV3W6

Avadí A, Dosso M, Ouedraogo R (2024) Données techniques et socio-économiques des producteurs maraîchers dans 4 villes Ivoiriennes, 2023. Yamoussoukro, CIRAD Dataverse, V1. https://doi.org/10.18167/DVN1/HG0DNY

Bancal V, Tano K (2019) Etude des Modalités de Réduction des Pertes Après Récolte dans les Cultures Maraichères en Côte d 'Ivoire. Rapport d'Expertise. PS n°010/FIRCA/DCARA/PRO2M/2018. Montpellier, CIRAD. https://agritrop.cirad.fr/598088/

Basset-Mens C, Avadí A, Acosta-Alba I, et al (2021) Life Cycle Assessment of agri-food systems. An operational guide dedicated to developing and emerging economies. Quae, Versailles

Belmin R, Malézieux E, Basset-Mens C et al (2022) Designing agroecological systems across scales: a new analytical framework. Agron Sustain Dev 42:1–18. https://doi.org/10.1007/s13593-021-00741-9

Biard Y, Basset-Mens C, Bessou C, Payen S, Benoist A, Avadí A, Tran T, Vigne M (2011) LCA-CIRAD platform: life cycle assessment of tropical agricultural products. https://doi.org/10.18167/INFRASTRUCTURE/00008

Bourbonnais R (2021) Économétrie. Collection Eco Sup. Dunod, 11 ème éd., mars 2021

Coste G, Biard Y, Roux P, Hélias A (2021) ELDAM: A Python software for Life Cycle Inventory data management. J Open Source Softw 6:2765. https://doi.org/10.21105/joss.02765

Coulibaly TH (2017) Projets de développement agricole et mutations du paysage agraire en pays Kiembara (Nord de la Côte d'Ivoire). Thèse de Doctorat unique, Université Félix Houphouët Boigny d'Abidjan – Cocody (Côte d'Ivoire), p 288

Dalgaard T, Hutchings NJ, Porter JR (2003) Agroecology, scaling and interdisciplinarity. Agric Ecosyst Environ 100:39–51. https://doi.org/10.1016/S0167-8809(03)00152-X

de Bon H, Fondio L, Dugué P, Coulibali Z, Biard Y (2019) Etude d'identification et analyse des contraintes à la production maraîchère selon les grandes zones agro-climatiques de la Côte d'Ivoire PS n°009/FIRCA/DCARA/PRO2M/2018. Rapport d'expertise. https://agritrop.cirad.fr/591600/

Dijkman TJ, Birkved M, Hauschild MZ (2012) PestLCI 2.0: A second generation model for estimating emissions of pesticides from arable land in LCA. Int J Life Cycle Assess 17:973–986. https://doi.org/10.1007/s11367-012-0439-2

Diwakar R (2017) An evaluation of normal versus lognormal distribution in data description and empirical analysis. Pract Assessment, Res Eval 22:1–15

Dosso M, Koffi A, Glou Bi I, Avadí A (2023) Analyse fonctionnelle de la filière maraîchère périurbaine en Côte d'Ivoire (2021–2022). Yamoussoukro, European Union - Cirad, p 138. https://agritrop.cirad.fr/604682/

Dosso M, Nandjui J, Avadí A (2024) Understanding the Ivorian market vegetables production: is the agroecological transition the right strategy? Agric Syst 218:16. https://doi.org/10.1016/j.agsy.2024.103971

Drabo E, Waongo A, Traoré F et al (2022) Effectiveness of combining bioacaricides with sprinkler irrigation to control the red spider mite, Tetranychus evansi Baker and Pritchard (Acari: Tetranychidae), in irrigated tomato crops in Burkina Faso, West Africa. J Entomol Acarol Res 54.https://doi.org/10.4081/jear.2022.10055

Fabre P, Dabat M-H, Orlandoni O (2021) Note Méthodologique Pour l'Analyse des Chaînes de Valeur Agricoles. Cadre et Outils - Elements Clés. Version 2. Paris, Agrinatura EEIG, p 43. https://agritrop.cirad.fr/607105/

FAO (2023) Tracking progress on food and agriculture-related SDG indicators 2023. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/cc7088en

Faure G, Chiffoleau Y, Goulet F et al (2018) Innovation and development in agricultural and food systems, Quae, Versilles. https://doi.org/10.35690/978-2-7592-2960-4

Foster RG (2005) Revised Universal Soil Loss Equation – Version 2 (RUSLE2). USDA – Agricultural Research Service, Washington D.C., USA

Greene WH, Schlacther D, Azomahou T (2011) Économétrie. 7e édition. Paris, Pearson Education

Heijungs R (2023) Analysis and remediation of the confusing specification of the lognormal distribution. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-023-02249-8

Hergoualc'h K, Akiyama H, Bernoux M, Chirnda N, del Prado A, Kasimr A, Dougla J, Ogle SM, Regina K, van dr Weerden TJ (2019) Chapter 11: N2O emissions from managed soils, and CO2 emissions from lime and urea application. In: Calvo Buendia E, Tanabe K, Kranjc A, et al (eds) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use. Switzerland, Intergovernmental Panel on Climate Change (IPCC)

Hollinger F, Staatz JM (2015) Agricultural growth in West Africa: market and policy drivers. FAO and the African Development Bank, Rome. https://openknowledge.fao.org/handle/20.500.14283/i4337e

Huijbregts M, Steinmann ZJN, Elshout PMF, Stam G, Verns F, Vieira MDM, van Zelm R (2016) ReCiPe 2016 a harmonized life cycle impact assessment method at midpoint and endpoint level. Characterization. Department of Environmental Science, Radboud University Nijmegen, Report I. https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

Hutchings N, Webb J, Amon B (2019) 3.D Crop production and agricultural soils. In: EMEP/EEA air pollutant emission inventory guidebook 2019. Luxembourg, Publications Office of the European Union, p 38. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/4-agriculture/3-d-crop-production-and/at_download/file

IOM (2020) Migration and agroecology in West Africa. Geneva, International Organization for Migration (IOM). https://publications.iom.int/books/migration-and-agroecology-west-africa

Koffi-Didia MA (2015) L' accès Au Foncier Urbain Et Périurbain Pour Le Maraîchage À Abidjan Et Ses Environs. Rev Géographie d'ENvironnement 2:47–54

Kone N, Asare-Bediako E, Koita O et al (2017) Seasonal and spatial variation in the prevalence of viral diseases and associated aphid-borne viruses in cucurbits in Cote d'Ivoire. Ann Agric Sci 62:227–234. https://doi.org/10.1016/j.aoas.2017.12.005

Kouame AR, Vei KN, Yao NR (2017) La production maraîchère periubaine à Bouaké: Dynamisme des acteurs et fonctions. Rev Ivoirienne Géographie des Savanes 1:66–77

Kra KV (2018) Problématique Maraîchère Induite Par La Nouvelle Dynamique Foncière Autour Des Bas-Fonds Urbains À Bouaké (Côte D'ivoire). Eur Sci Journal, ESJ 14:217. https://doi.org/10.19044/esj.2018.v14n15p217

Limpert E, Stahel WA, Abbt M (2001) Log-normal distributions across the sciences: keys and clues. Bioscience 51:341–352. https://doi.org/10.1641/0006-3568(2001)051[0341:LNDATS]2.0.CO;2

Malekpour S, Allen C, Sagar A et al (2023) What scientists need to do to accelerate progress on the SDGs. Nature 621:250–254. https://doi.org/10.1038/d41586-023-02808-x

Mambe-Ani P, Ouattara KN, Elleingand FE, Kadjo V (2019) Assessment of the impact of pesticide use in urban and periurban agriculture in Abidjan, Côte d'Ivoire. Int J Biol Chem Sci 13:2824. https://doi.org/10.4314/ijbcs.v13i6.32

Martin T, Assogba-Komlan F, Houndete T et al (2006) Efficacy of mosquito netting for sustainable small holders' cabbage production in Africa. J Econ Entomol 99:450–454. https://doi.org/10.1093/jee/99.2.450

Mottet A, Bicksler A, Lucantoni D et al (2020) Assessing Transitions to Sustainable Agricultural and Food Systems: A Tool for Agroecology Performance Evaluation (TAPE). Front Sustain Food Syst 4:1–21. https://doi.org/10.3389/fsufs.2020.579154

Nemecek T, Antón A, Basset-Mens C, Gentil-Sergent C, Renaud-Gentié C, Melero C, Naviaux P, Peña N, Roux P, Fantke P (2022) Operationalising emission and toxicity modelling of pesticides in LCA, the OLCA-Pest project contribution. Int J Life Cycle Assess 527–542. https://doi.org/10.1007/s11367-022-02048-7

Ouedraogo R, Montginoul M, Barbier B (2024) Farmers' behavior and innovations' adoption processes in rural Sahel: case of supplemental irrigation from farm ponds in Burkina Faso. J Rural Community Dev 19:80–104

Ouedraogo R, Bamba Y, Angbo-Kouakou E, Martin T, Wane A (2025) In: Abdelhaq H, Rémi K, Redouane C-A (ed) Proceedings of the V All Africa Horticultural Congress - AAHC2024. Louvain, ISHS, p. 107–114. (Acta Horticulturae, 1422). All Africa Horticultural Congress (AAHC 2024). 5, 2024-02-26/2024-03-01, Marrakech (Maroc). https://doi.org/10.17660/ActaHortic.2025.1422.14

Oula PQ (2021) Analyse de l'efficacité économique des systèmes de production horticoles agro-écologiques en milieu urbain et périurbain en côte d'ivoire : cas de la tomate. Université Alassane Ouattara

Oula PQ, Martin T, Fondio L, Koné D, Djézou WB, Parrot L (2021) Les déterminants de l'usage inadapté des produits phytophamarceutiques en maraichage de contre saison en Côte d'Ivoire. In: 14 ème Journées de recherches en sciences scociales. INRAE, SFER, CIRAD. Clermond-Ferrand : SFER, pp. 1–15. Journées de recherches en sciences scociales (JRSS). 14, Clermond-Ferrand, France, 7 April 2021/8 April 2021

Prasuhn V (2006) Erfassung der PO4-Austräge für die Ökobilanzierung - SALCA-Phosphor. Agroescope Reckenholz 20. https://ira.agroscope.ch/de-CH/publication/44071

Puech C, Brulaire A, Paraiso J, Faloya V (2021) Collective design of innovative agroecological cropping systems for the industrial vegetable sector. Agric Syst 191:103153

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.r-project.org/index.html. Accesssed 15 June 2023

Sika PK (2020) Plaidoyer pour une utilisation rationnelle des pesticides dans le maraîchage en Côte d'Ivoire : Une approche de la communication pour le développement. Ziglôbitha, Revue des Arts, Linguistique, Littérature & Civilisations. Université Peleforo Gon Coulibaly – Côte d'Ivoire

Silue NL (2016) La monographie des cultures maraîchères de la zone urbaine de Korhogo. Mémoire de fin de cycle. Université Peleforo Gon Coulibaly

Tano BF, Abo K, Dembele A, Fondio L (2012) Systèmes de production et pratiques à risque en agriculture urbaine: Cas du maraîchage dans la ville de Yamoussoukro en Côte d'Ivoire. Int J Biol Chem Sci 5. https://doi.org/10.4314/ijbcs.v5i6.12

Traoré AJ-F (2022) Analyse socioéconomique de la chaîne de valeur des cultures maraîchères dans la zone de Korhogo. Korhogo : UPGC, 103 p. Mémoire professionnel : Management des entreprises et organisations agropastorales, Université Peleforo Gon Coulibaly. https://agritrop.cirad.fr/604171/

Vermeire M-L, Thiour-Mauprivez C, De CC (2024) Agroecological transition: towards a better understanding of the impact of ecology-based farming practices on soil microbial ecotoxicology. FEMS Microbiol Ecol. https://doi.org/10.1093/femsec/fiae031

Yapo IR, Mambo V, Alder AC et al (2016) Caractérisation saisonnière des eaux de puits à usage maraîchère et domestique de Korhogo (Côte d'Ivoire) Seasonal characterization of well water use for vegetable gardening and domestic usage in Korhogo (Côte d ' Ivoire). Int J Biol Chem Sci 10:1433–1449

Yeo KT, Fondio L, Kouakou Kouakou L et al (2022) Caractérisation et diversité des systèmes de productions maraîchères au centre (Bouaké) de la Côte d ' Ivoire en vue d ' une transition agroécologique. J Anim Plant Sci 52:9538–9551

Zampori L, Pant R (2019) Suggestions for updating the Product Environmental Footprint (PEF) method. EUR 29682 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/424613

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.