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A COMPUTATIONAL FRAMEWORK FOR FARM-LEVEL GREENHOUSE GAS EMISSION ESTIMATION TO ENSURE CLIMATE-RESILIENT ENVIRONMENTALLY FRIENDLY AGRICULTURE

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As the agricultural sector contributes approximately 20 % of global greenhouse gas (GHG) emissions from anthropogenic activities, there is an urgent need for accessible, scientifically validated, and at the same time user-friendly tools to quantify farm-level carbon footprints. This paper presents a lightweight computational framework – Farm Carbon Footprint Estimator – developed in pure C programming language, designed to estimate CO_2*-equivalent (*CO_{2e}*) emissions across multi-crop and livestock farming agricultural systems. By integrating emission factors from the IPCC 2019 Refinement and the FAO EX-ACT tools, the developed compact application provides a high-fidelity assessment of emissions originating from fertilizer application, fuel combustion, enteric fermentation, irrigation usage and pesticide application. The application logic for carbon footprint estimation is built based on the latest international recommendations and guidelines regarding* CO_2 *emission equivalents for different agricultural materials and activities. The application supports emission estimation for 10 major crops and such agrotechnological inputs as NPK fertilizers, manure, diesel fuel consumption, irrigation water usage, 8 common pesticides related emissions, as well as emissions connected with livestock methane for cattle, swine and poultry. Unlike cloud-dependent solutions, this offline-capable framework ensures data sovereignty and accessibility for farmers in regions with limited digital infrastructure. Furthermore, Farm Carbon Footprint Estimator is extremely lightweight, requires no installation and operates in the command line interface (CLI) mode on any personal*

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computer. The developed application is extremely important and useful to ensure that every farmer can perform localized, data-driven carbon accounting and participate in carbon credit markets. Rigorous evaluation of carbon footprint on each farm is an important step towards responsible usage of natural resources and provides the guarantee of environmentally friendly and ecologically safe agricultural activity within the framework of climate-smart agriculture.

Key words: *carbon footprint, climate-smart agriculture, environmental modeling, green economy, software.*

Лиховид П. В., Грановьска Л. М., Чабан В. О., Максимов Д. О. Методика розрахункової оцінки викидів парникових газів на рівні сільськогосподарського підприємства для забезпечення кліматично стійкого екологічно чистого сільського господарства

Враховуючи, що сільське господарство є джерелом приблизно 20 % світових викидів парникових газів (ПГ) внаслідок антропогенної діяльності, існує нагальна потреба в доступних, науково аргументованих та водночас зручних інструментах для кількісної оцінки вуглецевого сліду на рівні індивідуальних фермерських господарств. У цій статті представлено обчислювальну платформу – Farm Carbon Footprint Estimator – розроблену з використанням мови програмування C, призначену для оцінки викидів CO_2*-еквіваленту (*CO_{2e}*) у агросистемах, що поєднують у собі вирощування різних культур і тваринництво. Інтегруючи коефіцієнти викидів з інструментів IPCC Refinement 2019 та FAO EX-ACT, розроблений компактний програмний додаток забезпечує високоточну оцінку викидів, пов’язаних із внесенням добрив, застосуванням паливно-мастильних матеріалів, кишкової ферментації тварин, використання зрошення та застосування пестицидів. Логіка додатку для оцінки вуглецевого сліду побудована на основі останніх міжнародних рекомендацій та вказівок щодо еквівалентів викидів* CO_2 *для різних сільськогосподарських матеріалів та видів діяльності. Додаток підтримує оцінку викидів для 10 основних культур та таких агротехнологічних ресурсів, як NPK добрива, гній, споживання дизельного пального, використання зрошувальної води, 8 поширених пестицидів, а також викидів, пов’язаних з метановим слідом від великої рогатої худоби, свиней та птиці. На відміну від хмарно-залежних рішень, розроблена офлайн-платформа забезпечує конфіденційність та доступність даних для фермерів у регіонах з обмеженою цифровою інфраструктурою. Крім того, Farm Carbon Footprint Estimator надзвичайно легкий у користуванні, не потребує встановлення та працює в режимі командного рядка (CLI) на будь-якому персональному комп’ютері. Розроблений додаток є надзвичайно важливим та корисним, надаючи можливість кожному фермеру виконувати локалізований облік вуглецю на основі даних та брати участь у ринках вуглецевих кредитів. Ретельна оцінка вуглецевого сліду на кожному сільськогосподарському підприємстві є важливим кроком до відповідального використання природних ресурсів та забезпечує гарантію екологічно чистої та екологічно безпечної сільськогосподарської діяльності в рамках кліматично розумного сільського господарства.*

Ключові слова: *вуглецевий слід, кліматично орієнтоване сільське господарство, екологічне моделювання, зелена економіка, програмне забезпечення.*

Problem statement. Estimating the carbon footprint of agricultural activities is essential for climate change effects mitigation, sustainable farm management, rational natural resource use, credible policy and reasonable market decisions. Agriculture contributes about 18–20 % of global greenhouse gas emissions, including large shares of CH_4 and N_2O. Carbon footprint accounting reveals how much each practice (fertilizer system, tillage practice, irrigation patterns, livestock, etc.) adds to global warming [1]. This allows to identify the most harmful and dangerous practices with the highest contribution into global warming, as well as find the best agrotechnological options to make agriculture less carbon-emitting and more environmentally friendly and climate-smart [2]. Consistent, standardized carbon footprint estimation is needed to avoid misdirected agrarian policy and enable fair comparison across different agricultural systems (e.g., organic vs. conventional) [3].

For now, there are established and generally accepted guidelines for greenhouse gas emissions estimation from agricultural activities, for example, FAO-backed

Environmental eXternalities ACcounting Tool (or EX-ACT). This tool provides with a consistent standardized methodology to evaluate and track the carbon footprint of various agricultural interventions, identify climate impacts of agricultural practices, and take reasonable steps to mitigate adverse effects of agriculture on global warming and related climate challenges. However, this tool is not straightforward to use for everyone and requires special initial setting and corresponding expertise. Besides, it is developed for Windows-based machines, and users that have Linux or macOS based systems will face additional complications to run this program [4–6]. Therefore, the problem of low accessibility of robust (and at the same time easy-in-use) carbon footprint estimation for any participant of agricultural activities, is not resolved properly, as far as free tools provide limited scientific reasoning or limited capabilities across different agrotechnological interventions, and commercial tools are not affordable for everyone.

Analysis of recent research and publications. Accurate carbon footprint estimation requires complicated calculations (accounting numerous key parameters and metrics available in specialized databases) that are extremely time-consuming and require special costly expertise if performed manually. In this regard, many scientific groups in cooperation with software developers have studied the possibility of developing automated framework for carbon footprint estimation if different anthropogenic activities. For example, Mariette et al. (2022) developed and proposed a framework for the analysis of carbon footprint of research institutions and laboratories. The framework relies upon the open-source web application entitled "GES 1point5" and is designed to evaluate the greenhouse gas emissions from a department, research laboratory or a scientific group. The web framework was successfully tested for the scientific and research laboratories of France. It was established that this sector of the economy of France is responsible for about 479 tCO_2 equivalents per laboratory and 3.6 tCO_2 equivalents per researcher [7].

Another interesting example of software for carbon footprint estimation is a web application CFTPR – the tool developed to assess the CO_2 emissions in constructed wetlands. The tool provided calculations on the carbon footprint during the construction, operation, and demolition periods of the wetlands. Notwithstanding the fact that the tool provided comparatively high accuracy of estimation, it is not available anymore now [8]. The tool entitled "OERCO2 Tool", developed within the framework of OERCO2 project funded by Erasmus+ program, also aimed to estimate carbon footprint in the specific domain, namely, for residential buildings. The "OERCO2 Tool" software proved itself to be reliable after manual scientific evaluation by the experts in this field. The user-friendly interface of the tool allows sustainability evaluation of the residential buildings to be performed even by non-specialists. The application is available at https://co2tool.oerco2.eu/en-US [9].

$CICO_2e$ is another tool in the format of web application for carbon footprint estimation, this time – for computational activities evaluation. The program uses time series of carbon intensity data (based mainly on power consumption) to predict the values for certain hardware configurations under various runtimes and usage scenarios. The web application is available for free at https://cico2e.swc.rwth-aachen.de [10].

Moving the focus to agriculture, it should be stressed that there are not so many available software applications and tools to perform reliable carbon footprint estimation. However, several recent developments are worth to be mentioned. First, OFoot online tool for carbon footprint evaluation of organic farming deserves attention. Notwithstanding the fact of its local importance (the application was built and tested for organic farms located in the Pacific Northwest region), the application provides interesting approach to carbon emission and sequestration assessment through simulation modeling. The validation tests proved that OFoot is useful for data-driven decision making in organic farms [11].

Recent research revealed that among over 60 potentially useful tools for carbon footprint estimation in agriculture, only three could be reckoned as valuable and insightful, viz., AgRE Calc, Cool Farm Tool, and Solagro (JRC) Carbon Calculator. AgRE Calc follows mainly IPCC Tier 2 calculation methodology and is provided on commercial basis. Cool Farm Tool uses more robust and detailed methodology for greenhouse gases emissions estimation. The program goes beyond the IPCC Tier 1 and Tier 2 methodologies through the inclusion of indirect and direct N_2O emissions, as well as extended accounting emissions from mineral fertilizers and changes in soil carbon storage. Solagro (JRC) Carbon Calculator is probably the simplest tool from the methodological point of view, as it uses IPCC Tier 1 and simplified Tier 2 methods in its core, but on the other hand, this application is free to use. As for other available options, they were delisted by the researchers as less usable, robust or suitable for farming level [12].

Another interesting and practical tool for farm-level carbon footprint estimation was the Carbon Calculator developed within the MARS Project. The tool has been developed as a Microsoft Excel extension and a standalone PC application. Its user-friendly interface made the tool usage comfortable and simple, notwithstanding the robust scientific algorithms (the application logic basis contained international standards and technical requiremnets on life cycle assessment (LCA) and C foot printing) and comprehensive support of 10 livestock categories (cattle, sheep, swine, and poultry), more than 150 different crops. The only categories not included in the tool were rice, forestry, and fishery. Another advantage of the Carbon Calculator was that the tool suited for the farms of different sizes and systems (organic, conventional, integrated, conservation agriculture, etc.). Unfortunately, notwithstanding the fact that the tool had strong scientific basis, was reliable in estimations and got warm receipt from scientific community and farmers, the application is no more available to download and use [13].

The study by Keller et al. (2014) focused on the comparison of other three tools for agricultural carbon footprint estimation. The first tool was Cool Farm Tool – a globally applicable, farm-oriented greenhouse gas emissions assessment tool developed by the University of Aberdeen, Unilever, and the Sustainable Food Lab. The tool combines empirical models with farm-specific data to estimate emissions and identify key greenhouse gas hotspots under different management scenarios. The Bonsucro GHG calculator focuses on quantifying emissions from sugarcane, sugar, and ethanol production to assess compliance with the Bonsucro Production Standard. Developed with life-cycle data from the sugarcane sector, it aggregates farm-level information to produce mill-level emission estimates and support mitigation planning. As it is evident form the mentioned above, the functionality and usability of this tool is narrowed down. And the third tool was PalmGHG – a specialized instrument for evaluating emissions and carbon sequestration in palm oil production systems. Created by the RSPO GHG working group, it supports emission reduction, monitoring, and reporting at the mill and supply-chain levels. Though the tool is food for the palm oil production systems, it is useless beyond them. As a result of the comparative study, it was revealed that it is almost impossible to compare these tools and decide which one should be preferred over other. The calculation outcomes differed significantly, but the authors claim that it was impossible to determine what results are closer to "right" [14].

The Farming Systems Greenhouse Gas Emissions Calculator is another web-based tool that is worth mentioning. It is linked to the SOCRATES soil carbon model that allows users to estimate greenhouse gas emissions associated with different crop management practices. By selecting location, crops, tillage, and fertilizer inputs, the tool identifies key sources of the emissions, including soil carbon exchange, N_2O emissions, fuel and fertilizer related emissions, etc. It illustrates how management decisions, such as reduced tillage and lower nitrogen application, can significantly decrease overall greenhouse gas emissions in cropping systems [15].

Of course, numerous other carbon footprint calculators exist that are not discussed in this article. However, they are less widely used, often lack a strong scientific basis, and many are no longer updated or available for download or online use. Furthermore, most calculators and estimators have been developed for local applications only, for example, Cplan v0 for the UK, the Farming Enterprise GHG Calculator for Australia, the US Cropland GHG Calculator for the United States, and Climagri for France. A truly global scope is primarily offered by FAO-backed tool EX-ACT, CBP, and the Cool Farm Tool [16]. For this reason, it is neither practical nor necessary to review all tools that have ever been developed. At the same time, this observation clarifies the main objective of our study and development work.

Our **purpose** is to develop a scientifically robust, data-driven, cross-platform software application capable of performing operational carbon footprint estimation for farms engaged in crop or livestock production, regardless of geographic location or other constraints.

Materials and methods. The methodology of the Farm Carbon Footprint Estimator is based on a modular computational approach that integrates internationally recognized greenhouse gas accounting protocols with a high-performance, deterministic software architecture.

The application utilizes a bottom-up accounting approach, where total farm emissions (E_{Total}) are calculated as the sum of emissions from individual agricultural activities. The modeling logic adheres to the IPCC Tier 1 and Tier 2 guidelines (2006/2019 Refinement), applying the following general equation:

$$E_{Total} = \sum_{i=1}^{n} \left(A_i \times EF_i \times GWP_i \right), ,$$

where: A_i – activity data (kg of fertilizer per ha, L of fuels, etc.); EF_i – specific emission factor derived from the FAO EX-ACT and Ecoinvent databases; GWP_i – global warming potential used to convert non-CO_2 gases into CO_2 equivalents.

The framework accounts for the life-cycle emissions of mineral NPK fertilizers and organic manure. For nitrogenous fertilizers, the model calculates both the upstream manufacturing emissions and the direct-indirect nitrous oxide emissions resulting from field application. Pesticide emissions are calculated using specific emission factors for eight major active ingredients, accounting for the energy-intensive chemical synthesis processes. As for the energy and livestock components, the framework utilizes following principles:

– Fuel Combustion: Carbon intensity is calculated based on the net calorific value of diesel fuel used in machinery and transport.

– Enteric Fermentation: Methane emissions from livestock (cattle, swine, and poultry) are estimated based on population-specific emission factors provided by the FAO.

– Irrigation: Emissions are modeled based on the energy requirements for water pumping, assuming standard lift-height efficiencies and regional grid-emission factors.

The application supports a multi-crop architecture, allowing for the simultaneous analysis of up to ten distinct crop types (e.g., wheat, maize, soybean). The data ingestion layer is designed for versatility:

– Direct User Input: Interactive entry for real-time farm assessment.

– Batch Processing: Ingestion of Comma-Separated Values (CSV) files, enabling the analysis of large-scale historical datasets or multi-farm cooperative data.

The estimator is implemented in the C99 programming language, chosen for its deterministic execution and minimal hardware requirements. The software is partitioned into distinct functional modules to ensure scientific maintainability:

– compute.c: Contains the core mathematical logic for GHG stoichiometry.

– input.c: Handles the parsing and validation of agronomic data.

– report.c: Generates structured analytical reports, calculating both total emissions and per hectare intensity metrics.

To ensure accessibility in regions with limited digital infrastructure, the tool was engineered with zero external dependencies. It utilizes standard C libraries, allowing it to be compiled and executed on any operating system (Linux, macOS, Windows). The Command Line Interface (CLI) design ensures that the tool can run on legacy hardware or be integrated into automated server-side pipelines. The internal crop database (yielding parameters and nutrient requirements) was standardized against global averages to provide a reliable default baseline for users who lack specific soil-test data, while still allowing for manual override in advanced UI modes.

Results and discussion. The implementation of the Farm Carbon Footprint Estimator resulted in a multi-modal computational framework designed to maximize accessibility across diverse technical environments. The system provides several distinct operational modes, each optimized for specific user requirements while maintaining absolute algorithmic consistency.

1) Heuristic Interface Modes (Simple & Advanced UI): These modes facilitate real-time, interactive data entry. The Advanced mode utilizes standardized box-drawing character forms to provide visual feedback and color-coded results to reduce human error during the manual ingestion of agronomic variables.

2) Command Line Interface (CLI) and Batch Processing: For high-throughput research, the application supports a headless CLI mode. The Batch Mode is capable of direct Comma-Separated Values (CSV) file upload, allowing for the automated generation of carbon reports from existing farm management datasets.

3) System Portability: Testing confirmed that the zero-dependency C99 architecture ensures seamless cross-platform performance across Linux, macOS, and Windows. This robustness is critical for deploying the tool in localized field offices where modern hardware or internet connectivity may be absent.

A primary result of the development is the high-granularity processing capability of the created framework. The system successfully integrates emissions data from up to 10 distinct crop profiles within a single farm entity. The application utilizes two primary data structures to ensure interoperability with legacy and modern datasets (Table 1).

Table 1

Comparison of supported data ingestion formats

Feature	Legacy format	Multi-crop format
Scope	Single-crop aggregate	Detailed multi-crop breakdown
Primary utility	Rapid historical inventory	Precision management
Livestock support	Integrated	Secondary module
Pesticide analysis	General aggregate	ID-specific

The multi-crop format allows for the precision mapping of agrotechnological inputs – such as NPK fertilizers, manure, diesel fuel, and irrigation – to specific land parcels, enabling a more nuanced understanding of carbon intensity (tCO_2e/ha) across the farm enterprise. The framework produces a structured report, which disaggregates emissions into specific categories: fertilization, fuel, irrigation, pesticides, and livestock. For quantitative reporting the system automatically calculates emission intensity per hectare, providing a benchmark for sustainability. For automated mitigation logic, the system, based on the calculated tCO_2e/ha thresholds, generates targeted sustainability recommendations. For example, farms with low-intensity profiles (less than 2 tCO_2e/ha) are automatically labeled as “Sustainability Leaders” (Fig. 1).

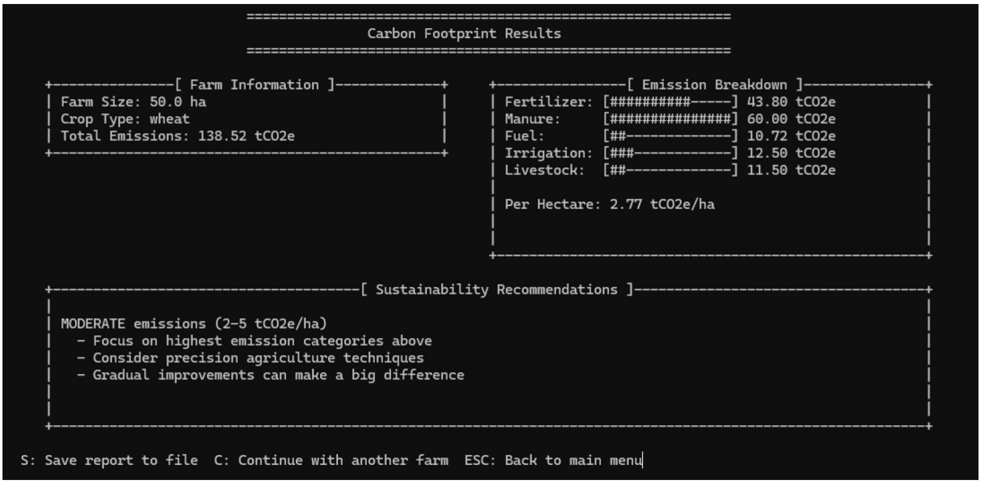

Fig. 1. User interface and sample report of the Farm Carbon Footprint Estimator

Rigorous testing via the “demo.sh” and “demo.bat” scripts across different operating systems verified that the internal calculation engine produces identical results regardless of the interface selected. The “Batch Mode” was successfully used to process a standardized multi_crop_sample.csv, demonstrating the tool’s readiness for large-scale longitudinal studies of agricultural emissions. The successful compilation using standard gcc with no external libraries validates the tool’s utility as a lightweight alternative to resource-heavy and internet connection dependent cloud platforms. The tool is available for download at the GitHub repository address: https://github.com/PavloICSA/CarbonFarm.

Conclusions and further prospects of research. Farm Carbon Footprint Estimator is a CLI cross-platform tool aimed to assist farmers in comprehensive evaluation of greenhouse gas emissions. The tool is based on the international databases of emission factors and scientifically substantiated computational logic. It is available for free and distributed upon the terms of MIT license. Further improvements will include significant extension of the available emission database, adding more features for detailed emissions tracking, multilingual support and, perhaps, deployment online in the form of a progressive web application.

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