The International Journal of Life Cycle Assessment (2026) 31:82
https://doi.org/10.1007/s11367-026-02651-y

LCA FOR AGRICULTURE

Uncovering the environmental burden of hops: a spatially resolved agricultural LCA for modern beer supply chains

Alberto Fraile[1] · Adrián Agraso-Otero[1] · Perrine Loussert[2] · Almudena Hospido[1] · Sara González-García[1]

Received: 19 December 2025 / Accepted: 15 April 2026

Abstract

Purpose With the expansion of microbreweries and rising demand for craft beer, attention has increasingly turned to hops (*Humulus lupulus*), a key brewing component that remains understudied from an environmental impact perspective. This study assesses the environmental burdens of hop production in a new French growing region, comparing organic and conventional systems under contrasting yield levels, and addressing whether GIS-based nutrient emission modelling improves the representation of spatial variability in agricultural Life Cycle Assessment (LCA).

Methods An attributional cradle to farm-gate LCA was conducted for hop production systems located in Aquitaine. 1 kg of dried hop cones before pelletization was chosen as the Functional Unit (FU). The perennial cycle was represented over a 20-year lifespan by distinguishing establishment and productive phases and normalizing total impacts by cumulative production. Impact categories included Global Warming (GW), Terrestrial Acidification (TA), Terrestrial and Freshwater Ecotoxicity (TET - FET), Freshwater Eutrophication for nitrogen (FEn) and phosphorus (FEp), and Water Scarcity (WS). Nutrient leaching was estimated with InVEST Nutrient Delivery Ratio (NDR) model and compared with conventional approaches.

Results and discussion Hop production was found to carry considerable environmental burdens, mainly driven by fertilization intensity, fuel-related field operations, and energy use during kilning. Organic low-yield systems showed the lowest impacts for GW and TA, whereas organic medium-yield systems exhibited markedly higher FE due to intensified nutrient inputs. Compared with U.S. benchmarks, French systems in new cropping regions showed roughly double carbon footprints due to low yields. At beer production level, hop use becomes environmentally significant in highly hopped craft styles (4–8 g/L) challenging the assumption that hops are negligible contributors. GIS-based nutrient modelling revealed that hydrological connectivity can substantially alter leaching estimates relative to conventional Tier I–II methods.

Conclusions Hop cultivation can entail relatively high environmental burdens per kilogram of product, particularly when yields are low. Enhancing yields while optimizing fertilizer inputs is therefore essential to reduce impacts in emerging growing regions. By integrating GIS-based emission modeling into LCA and disentangling N and P-driven eutrophication with regionalized factors, this study provides management-relevant evidence to support the optimization of fertilization strategies. It also offers a transferable framework for other agricultural systems in which nutrient losses are a major driver of environmental impacts.

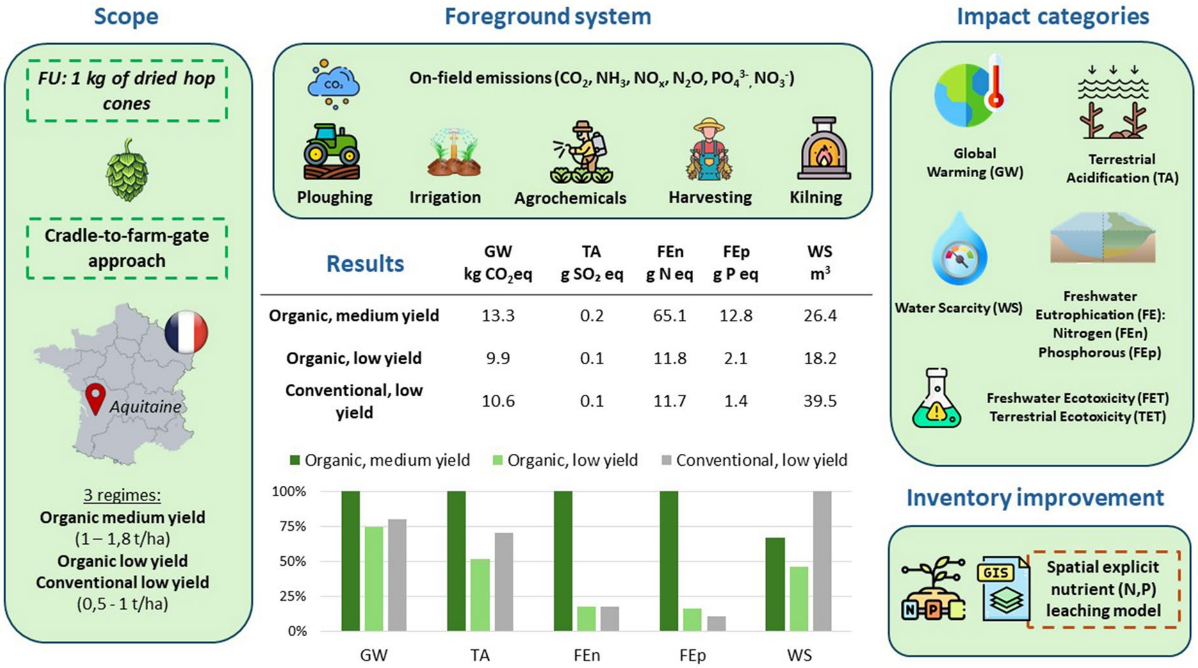
Communicated by: Matthias Finkbeiner

✉ Alberto Fraile
albertofraile.debenito@usc.es

[1] CRETUS, Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, Santiago de Compostela 15782, Spain

[2] HOPEN, Terre de Houblon, 156 avenue Jean Jaurès, Agen 47000, France

Graphical Abstract



Results	GW kg CO_2eq	TA g SO_2 eq	FEn g N eq	FEp g P eq	WS m^3
Organic, medium yield	13.3	0.2	65.1	12.8	26.4
Organic, low yield	9.9	0.1	11.8	2.1	18.2
Conventional, low yield	10.6	0.1	11.7	1.4	39.5

Keywords Hop · Sustainable agriculture · Life cycle assessment · GIS modeling · Nutrient leaching

1 Introduction

Agricultural production is a key driver of resource use, water pollution and greenhouse gas (GHG) emissions. For example, agriculture accounts for 72% of freshwater withdrawals worldwide (FAO 2021), contributes to 2/3 of global nutrient loads in surface water streams (Yang 2022), and 22% of GHG emissions can be attributed to agriculture, forestry and land use (IPCC. Intergovernmental Panel for Climate Change, Arias and Bellouin 2021). As such, a detailed quantification of impacts and mitigation options is of crucial relevance, so informed choices can be made at the supply chain (Nemecek et al. 2024). Life Cycle Assessment (LCA) is the preferred approach for evaluating the environmental impact of the agri-food supply chains (Clark and Tilman 2017; Thoma et al. 2022). Its application has been crucial in the current understanding of which phases of the production cycle of food systems have the greatest impacts and how they can be improved to be more sustainable (Poore and Nemecek 2018). By accounting for different life cycle phases, shifts in environmental burdens between life cycle stages can be avoided.

Beer is the fifth most consumed beverage in the world besides tea, carbonated soft drinks, milk and coffee, and it continues to be a popular drink with an average annual consumption of 8.6 L per capita by population aged above 18 (OECD 2023). Hops (*Humulus lupulus*), a key ingredient in beer, are primarily used for their aroma and bittering properties. While the hop industry plays a key role in the beer supply chain, there is little scientific consensus on how much this crop contributes to GHG emissions (Sipperly and Ziegler 2014) or how sustainable its production is.

When it comes to their influence on beer's flavor and bitterness, hop varieties can be classified in two categories: alpha hops and aroma hops (Oladokun et al. 2017). While traditional hop production has focused on alpha hops for massive production of light beer, the popularization of craft beer and beer styles such as Pale Ales (PA) and India Pale Ales (IPA) has led to an increase in the cultivation of aroma hop varieties beginning in the 90s (Almaguer et al. 2014). Although hops are used in much smaller quantities compared to other key ingredients like barley or wheat, their impact on flavor is significant. For example, lighter beers such as Lagers typically contain between 0.5 to 3 grams of hops per liter. In contrast, hopped styles, such as IPAs, Stouts, or some Pilsners, generally range from 4 to 16 g/L, with extreme hopped beers reaching concentrations up to 22 g/L (Lafontaine and Shellhammer 2018; Klimczak et al. 2023).

Besides this contrasting hop intensity among beers, most environmental analyses that include hops evaluate them indirectly within brewing LCAs using beer as the functional unit (Mattila et al. 2012; Amienyo and Azapagic 2016; McDonagh et al. 2024) and to the best of our knowledge, only one peer-reviewed carbon footprint study has specifically addressed hop cultivation under the LCA framework (Hauser 2019). Under this approach, hop-related impacts are generally considered negligible (due to the typical low hop concentration of conventional Lager-style beers) resulting in minimal estimated impacts (Beverage Industry Environmental Roundtable 2012), or initially excluded from the scope (Saget et al. 2022). However, in recent decades, beer production has shifted from large-scale uniform output (American Lager) towards many smaller producers making diverse craft styles. This change is driven by a shift in consumer tastes and trends such as the rise of the "buy local" movement (Cabras et al. 2023). The growth of breweries in the U.S. illustrates this trend: from just 48 breweries in 1981 to about 1700 by 2011, reaching 9612 operating craft breweries in 2024 (Dighe 2017; Gribbins 2025). This is also happening in Europe. French hop production has seen renewed interest mainly due to the rise of microbreweries. France now has around 2500 breweries, the most in Europe, and consumes 68% of its own beer (Coulon 2024). Historically, hop production in France was concentrated in the Alsace region, but the recent rise of microbreweries has driven expansion into new areas, such as Aquitaine. French annual production is about 940 t, less than 1% of global hop output (≈113 mt), a market dominated by Germany and the U.S., with a 41% and a 35% of world share respectively (BH 2024). Still, this shift in beer production has boosted demand for local and organic hops, making France one of the few countries where a significant share (around 30%) is dedicated to organic hop farming. Though small in volume (around 200 t in 2024), this organic production is valued for its high quality (Ruggeri et al. 2024). Despite the land dedicated to hop production is expected to keep increasing in the next years (BH 2024), specific environmental data for hop cultivation remains scarce, especially for new growing regions and organic systems. Moreover, previously environmental assessments on beer production are not reflecting current practices on the brewing supply chain (i.e. hop concentration) or variability among producing regions (US and Europe).

LCA allows for the systematic evaluation of environmental impacts along the production chain, including raw material extraction, processing and transport, as well as on field agricultural emissions and land use change impacts. However, agricultural systems inherently exhibit high levels of spatial variability, which are influenced not only by farm management but also by environmental variables such as soil type, topography, and local climate, playing a critical role in determining inputs such as fuel consumption or water demands. While farmers have limited influence over pedoclimatic conditions, representing them accurately is essential for improving the robustness of LCA studies. For example, determining the most suitable fertilizer dose is particularly challenging due to differing nutrient requirements driven by variations in soil quality between fields and among farms (Senske et al. 2020). Additionally, pedoclimatic conditions influence environmental outcomes, including nutrient leaching and gaseous emissions (Lee et al. 2020). This is particularly relevant for nitrogen (N) management, as around 50% of the N applied to agricultural soils is not absorbed by crop plants, with a significant fraction instead immobilized by the soil microbiome (Liu et al. 2016). N losses occur through various pathways, including direct emissions as nitrous oxide (N_2O), volatilization as ammonia (NH_3) and nitrogen oxides (NO_x), and leaching of nitrates (NO_3^-) into water bodies (Pan et al. 2016; Wowra et al. 2021). These processes make fertilization a major driver of environmental impacts in agricultural systems, particularly for impact categories such as freshwater eutrophication, terrestrial acidification, and climate change (Singh et al. 2024).

As real-measured data for on-field emissions (i.e. leaching or gaseous) is resource intensive, if often inaccessible, LCA relies on emission factors. Those are an efficient, standardized, and broadly applicable way to assess agricultural emissions (Adewale et al. 2018). Tier I models use generic emission factors, simplifying assumptions, while Tier II models use national emission factors (in some cases, at regional level) specific to the activity, with more complex assumptions. Tier III methods are based on mechanistic models and high-quality data. The combination of different models and tools provides a potential way to address spatial variability, but it can lead to inconsistencies. Mechanistic simulation models (Tier III) can help analyze specific processes. However, they are often too complex and therefore the use in LCA is limited (Avadí et al. 2022). They require a large amount of input data, which is often unavailable for a given application. Additionally, combining multiple simulation models generally exceeds the scope of a project (Nemecek et al. 2024). Therefore, medium-complexity models (Tier II) normally offer the best trade off: they are detailed enough to assess mitigation options and account for the main influences of pedoclimatic conditions, yet they are also scalable and require a moderate amount of data (Knuchel et al. 2009). Recent advances highlight the potential of integrating Geographic Information Systems (GIS) into LCA frameworks to better represent spatial heterogeneity in agricultural systems (Pfister et al. 2020; Kaita and Harun 2023; Shi and Yan 2024). GIS are widely used to assist policy makers in spatial planning by combining data from different sources, such as satellite images, land use land cover (LULC) data, and field data within advanced algorithm models (González et al. 2011; Grieco et al. 2024, 2025). However, within the context of LCA, their application remains limited, despite their potential to represent significant advancement in emission modeling in agroecosystems (Chaplin-Kramer et al. 2017).

This study focuses on addressing mentioned gaps: (i) providing primary-data-based environmental profiles of hop production, (ii) comparing conventional and organic regimes under different yield levels, and (iii) integrating GIS emission modelling within the LCA framework to better capture spatial variability among crops. To achieve this, we conducted an attributional LCA of hop production based on data collected directly from farmers in Aquitaine, a new hop production region in France, under different scenarios. Each scenario was evaluated across multiple impact categories commonly applied in agricultural LCAs. Results were then stratified by yield levels and by production regime (conventional vs. organic) and compared with findings from previous studies. A brief discussion on nutrient leaching emission models was included to assess differences between the applied GIS model and two traditional LCA approaches. Finally, we offer potential strategies to reduce the environmental burdens associated with hop cultivation, as well as implications for the beer supply chain.

2 Materials and methods

2.1 Study area and scenarios

This study was carried out in collaboration with HOPEN, a hop trader cooperating with a group of hop producers established in Aquitaine region. Farms under study are distributed across middle and southwest France (Fig. 1).

Aquitaine is characterized by a temperate climate with warm summers and constant rainfall (800–1300 mm) throughout the year (The Climate Data 2025). Croplands under study were dedicated to agriculture in the last 20 years, producing arable crops, mainly orchards. A mix of hop varieties is cultivated on each farm: *Nugget, Willamette, Cascade, Chinook, Mount Hood or Babe Rouge* among others. Two production regimes were assessed: organic and conventional. Due to the availability of representative data, and the growing interest in organic hop cultivation, four scenarios were defined for the organic regime (O-1 to O-4), and one for the conventional regime (C-1). All the scenarios differ in terms of use of agrochemicals (including mineral and organic fertilizers and phytosanitary such as herbicides, fungicides and insecticides) and biomass yields (Table 1).

Conventional production relies on mineral fertilizer, such as ammonium nitrate, and synthetic chemical pesticides, including herbicides like Fluazifop-P[1] and aluminum-based plant protection products. In contrast, organic regimes use amendments derived from composted manure and organic residues. Pest and disease management in organic regimes is restricted to substances approved under organic certification standards. For instance, copper-based fungicides are permitted but strictly regulated, with a maximum application rate of 28 $kg \cdot ha^{-1}$ over a seven-year period (EC 834/2007).

2.2 Cultivation systems

Female hop plants are planted using rhizomes in fields with 7.5–8 m high trellises composed of wooden posts and steel wires that form rows with vertical strings (cocoa fiber) from the ground to the trellis. 1 ha of hopyards is composed of 100–120 posts with approximately 10 plants per post, spaced in a 1.1 × 3.2 m pattern. Fertilization and soil preparation are carried out between March and May. From June to August, drip irrigation is implemented to support optimal crop establishment. Pest treatments are conducted from March to August. The harvest begins between late August and mid-September, when cones reach maturity. To remove the plants, bottom-cutting tractors first cut the twine at the base, leaving the plants hanging from the trellises to start drying. Then, top-cutting tractors cut the twine at the top, dropping the plants into a following truck. Harvesting machines separate cones from the rest of the plant. At this stage, the moisture content in the hop cones is approximately 75–80% (Oladokun et al. 2017). Because hops need to be preserved postharvest, they are kilned at 55 °C for 6–9 hours depending on the variety, until they dry to about 10% moisture. After cooling for 24 hours, the dried cones are wrapped in burlap or polyethylene bags and loaded onto trucks. To prevent oxidation and facilitate its use, dried cones are pelletized and stored in bags with controlled atmosphere.

2.3 Environmental assessment

Attributional LCA methodology was applied in accordance with the guidelines established in ISO 14040 and ISO 14044 (ISO 2021a, b) (Fig. 2). In attributional LCA, all inputs and outputs of a production system are attributed to the functional unit by linking and/or partitioning the unit processes of the system according to normative rules (e.g., allocation factors based on economic, mass or energy values, among others).

The environmental performance is quantified by the following impact categories with high importance in the agricultural sector (Alhashim et al. 2021): Global Warming (GW), Terrestrial Acidification (TA), Terrestrial Ecotoxicity

---

[1] Common name for: (2*R*)-2-(4-([5-(trifluoromethyl)pyridin-2-yl]oxy)phenoxy)propanoic acid

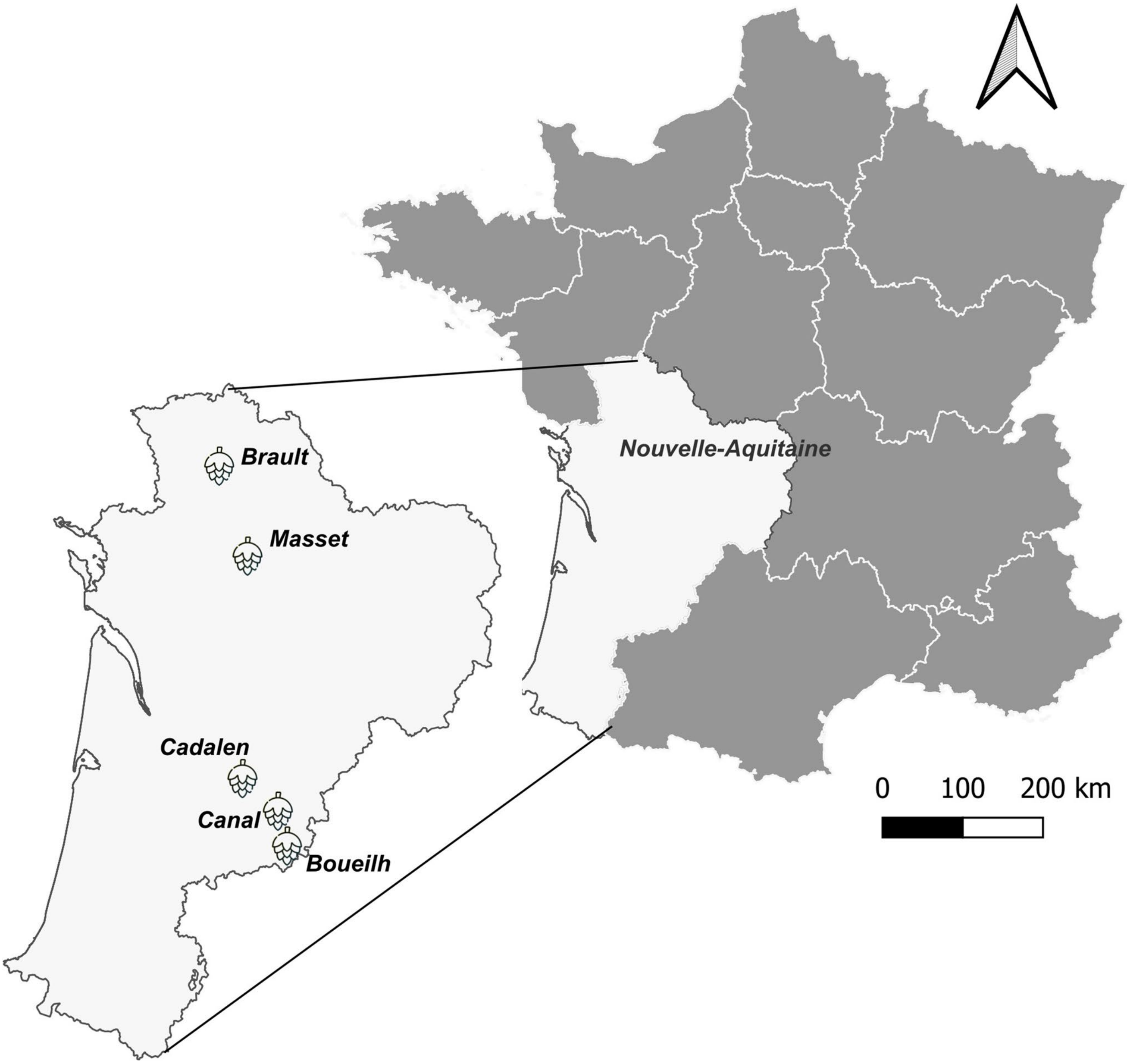


Fig. 1 Distribution of the assessed hop producers in Nouvelle-Aquitaine region of France. (O= organic, C= conventional). Brault = O-1; Masset = O-2; Canal = O-3; boueilh = O-4; cadalen = C-1

(TET) and Freshwater Ecotoxicity (FET); which were quantified using ReCiPe 2016 v 0.9 Hierarchist Midpoint method (Huijbregts et al. 2017). Besides, some widely used impact assessment frameworks in LCA, such as ReCiPe2016, LC-IMPACT (Verones et al. 2020), or IMPACT World+ (Bulle et al. 2019), provide spatially applicable CFs for a range of categories, including freshwater eutrophication, these models typically assume phosphorus as the sole limiting nutrient in freshwater systems, neglecting the numerous freshwater systems across the world where eutrophication in freshwater is co-limited by N and P or even N-limited (Elsaholi and Kelly-Quinn 2013; Zhou et al. 2022). To address this limitation, Freshwater Eutrophication for nitrogen (FEn) and Freshwater Eutrophication for phosphorus (FEp) were quantified by applying characterization factors (CFs) developed by Payen et al. (2021), which are spatially differentiated for France and include both dissolved inorganic N and dissolved inorganic P fate factors applied for nutrients export by rivers. Finally, Water Scarcity (WS) was assessed using the AWARE method v1.06 (Boulay et al. 2018) because it considers not only water consumption but also regional water availability. All these indicators were evaluated with SimaPro® software v 9.6 (Pré Sustainability 2022).

Table 1 Scenario description. O= organic, C= conventional. Brault=O-1; Masset=O-2; Canal=O-3; boueilh=O-4; cadalen=C-1. Yield classification was conducted considering ranges of 1.4 to 2.4 t of dried hop cones·ha^{-1}, which are typical yields for hop production in Europe, according to Rossini et al. (2021). Note that some farms exhibit performance variability, as several fields within each farm were assessed under different production levels

Scenario	Fertilization strategy (kg·ha^{-1} ·yr^{-1})	Phytosanitary	Average yield (kg dried cones·ha^{-1} ·yr^{-1})
O-1	N ≈ 300; $p \approx 500$	Copper-based fungicides and organic treatments	Medium: 1459
O-2	N ≈ 24; $p=0$	Organic treatments	Low: 832 ± 355
O-3	N ≈ 190; P ≈ 30	Organic treatments	Low: 475 ± 221
O-4	N ≈ 240; P ≈ 24	Organic treatments	Medium: 1502 ± 804
C-1	N ≈ 175; P ≈ 3	Synthetic herbicides, fungicides and insecticides	Low: 641

2.3.1 Scope and system boundaries

The functional unit (FU) serves as the reference unit for calculating all inputs and outputs within the system under study. 1 kg of dried hop cones (10% moisture) before pelletization was used as the FU. This mass-based unit gives breweries an idea of how to manage their supplies to minimize environmental impacts associated with beer production, and farmers can adapt their agronomic practices while integrating productivity metrics. To conduct the assessment, a cradle-to-farm gate approach was followed (Fig. 3) including within the system boundaries: raw material extraction (e.g., fossil fuels, minerals), agrochemicals production, machinery production and maintenance, all field operations carried out (including trellis installation, soil preparation, fertilizer and phytosanitary application, pruning and harvesting) and kilning (i.e. drying hop cones in industrial oven).

The perennial cycle of hop cultivation was modelled over a 20-year lifespan. The establishment phase (Year 0–1) was modelled using scenario-specific establishment data, including trellis installation, planting operations, and first-year input requirements. The productive phase (Years 1–20) was represented using farm data collected for the year 2024 replicated across years. Total inputs and emissions were aggregated over the entire lifespan and normalized by cumulative hop production to express impacts per FU. Yield performance was obtained from data collected over four years of production. To project yields over a 20-year period, the same modeling approach was applied to all systems, based on a typical progression in which maximum yield is reached by year 4, maintained until year 8, and then gradually declines (Magadán et al. 2011; Rossini et al. 2021) to better represent perennial cycle in the LCA framework (Bessou et al. 2013). However, changes in input demands (and derived emissions) or potential impacts from pests, diseases, and climate change over the 20-year span, were not considered in this projection. No allocation to residues from the plants is performed, as they are shredded and deposited into the soil (acting as an organic amendment).

2.3.2 Life cycle inventory

Operations and requirements of the crops are different in the first year than in the following ones. The life cycle inventory data for the foreground system (direct agricultural inputs) such as primary and site-specific data (information concerning tractors and implements, labor hours and input rates) for all case studies were directly collected on the farms by means of surveys and interviews with farmers. Secondary data regarding the production of the different agricultural inputs were taken from ecoinvent® v3.10 database (ecoinvent 2023) and complemented with Agri-footprint v6.3 database for specific purposes (Blonk Consultants 2022). Table SM 1 and Table SM 2 in the supplementary materials summarize inventory data related to the cultivation systems associated with 1 ha of cultivated system for the year 0 and years 1 to 20 respectively, including dataset description of background processes.

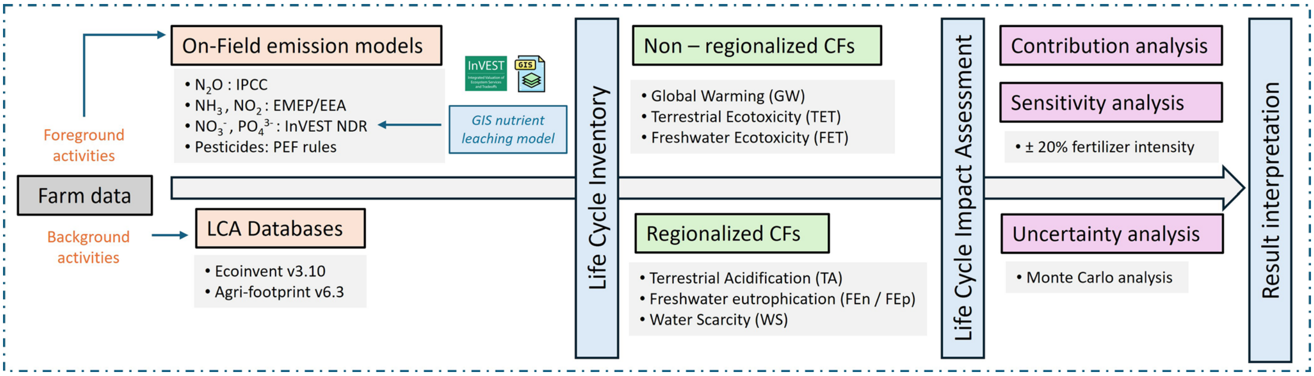


Fig. 2 Technical roadmap of environmental analysis. CFs = characterization factors

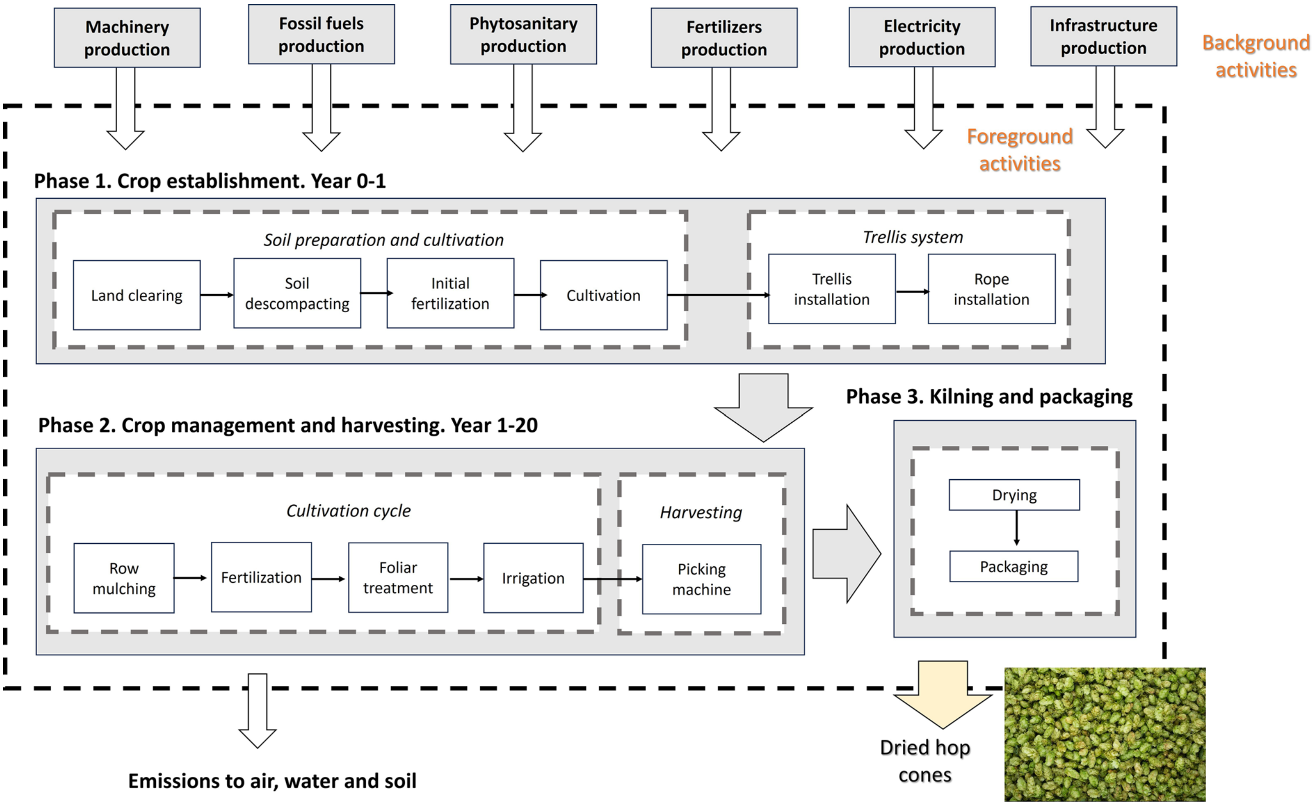


Fig. 3 Scheme of the system boundaries

2.3.2.1 On field emissions and nutrient leaching model Several empirical models are employed to estimate field emissions resulting from application of mineral fertilizers, organic amendments (including pruning residues) and phytosanitary treatments (Fig. 2): IPCC Guidelines for National GHG Inventories, which are used to quantify direct and indirect N_2O emissions (IPCC 2019a); the European Environment Agency (EEA) and the European Monitoring and Evaluation Program (EMEP/EEA 2023) for the emissions of NO_2 and NH_3.

The InVEST® Nutrient Delivery Ratio (NDR) model v3.14.3 (Natural Capital Project 2024) was used to assess crop´s capacity to buffer nutrient loads associated with fertilization. The model enabled us to compare the resulting NO_3^- and PO_4^{3-} loads reaching nearby surface water bodies, thereby improving the accuracy and resolution of the life cycle inventory. The model computes a nutrient mass balance based on (i) the nutrient loading rates associated with the crops in the landscape, and (ii) the retention properties of different Land Use (LU) classes belonging to the same flow path. Next, the model uses topographic routing and an index, the NDR factor, to emulate the movement of nutrients across the landscape and into a watercourse. The NDR factor is calculated for each "landscape cell" based on the properties (e.g. slope, retention coefficient, quick flow events, hydrologic balance, etc.) of cells that belong to the same flow path. At the catchment outlet, the nutrient export to water is calculated as the sum of the cell-level contributions. A detailed description of the model can be found in Redhead et al. (2018) and Natural Capital Project (2024). Sources of all the inputs required for the simulation of this model are provided in Table SM 3. Also, simulation inputs and outputs for each scenario are provided in Table SM 4 in the supplementary materials. For discussion purposes (Sect. 4.2.), two alternative nitrogen leaching estimation approaches were independently implemented in Microsoft Excel: IPCC Tier I approach (IPCC 2019b) and SQCB Tier II approach (Ziep et al. 2009).

To estimate the emissions of active ingredients associated with the use of different phytosanitary products into air, water and soil, the European Commission's Product Environmental Footprint Category Rules (European Commission 2017) were applied. Following this framework, primary distribution of active ingredients was assumed as 9% to air, 1% to water, and 90% to soil.

3 Environmental results

3.1 Contributing activities to environmental profiles

The environmental profiles, as displayed in Fig. 4, are distributed in six big contributing factors: *Irrigation* includes water extracted from natural sources and the drip-irrigation system (mainly pipes, pumps and electricity); *Field operations* include all activities related to machinery and diesel provision, as well as diesel on field emissions; both *Fertilizers* and *Phytosanitary* include input acquisition and post-use emissions; *Infrastructure* is composed of trellis system (which includes wood posts, creosote treatment, steel elements and ropes); *Kilning* process includes industrial oven and fuel acquisition, as well as emissions resulting from burning propane or diesel (depending on the farm).

Field operations, fertilizers and kilning are the main contributors to GW across all systems. However, their relative influence varies among scenarios. Systems O-3, O-4, and C-1 share similar GW profiles, with field operations contributing from 36 to 45%, fertilizers ranging 28–37%, and kilning 18–23%. In contrast, O-1 is clearly fertilizer dominated (50% of total GW impact), followed by kilning (30%), and field operations playing a minor role (14%). On the other side, O-2 shows a distinct order: where field operations (41%) and kilning (39%) dominate, while fertilizers contribute only 7%, reflecting its reduced nitrogen input intensity. Minor contributions from phytosanitary products, infrastructure, and irrigation are consistent across all systems. Electrification presents a promising opportunity to decouple the kilning process from carbon-intensive energy sources, as electric kilns appear to offer greater energy efficiency and can be powered with solar energy (Cinardi et al. 2025).

TA impact is mainly driven by fertilizer use, with marked consistency in four out of the five systems analyzed. TA is primarily associated with the release of acidifying substances such as NH_3 or NO_x, which volatilize into the atmosphere and are later deposited into soils, leading to acidification of terrestrial ecosystems. Fertilizers contributed between 82 and 87% of the total TA impact in O-1, O-3, O-4, and C1. This is largely attributed to two stages: the upstream production, and the field application phase. The latter is generally the main source of agricultural NH_3 emissions. Secondary contributions in these systems come from field operations (4–14%) and kilning (1–8%), mostly due to the combustion of fossil fuels generating acidifying

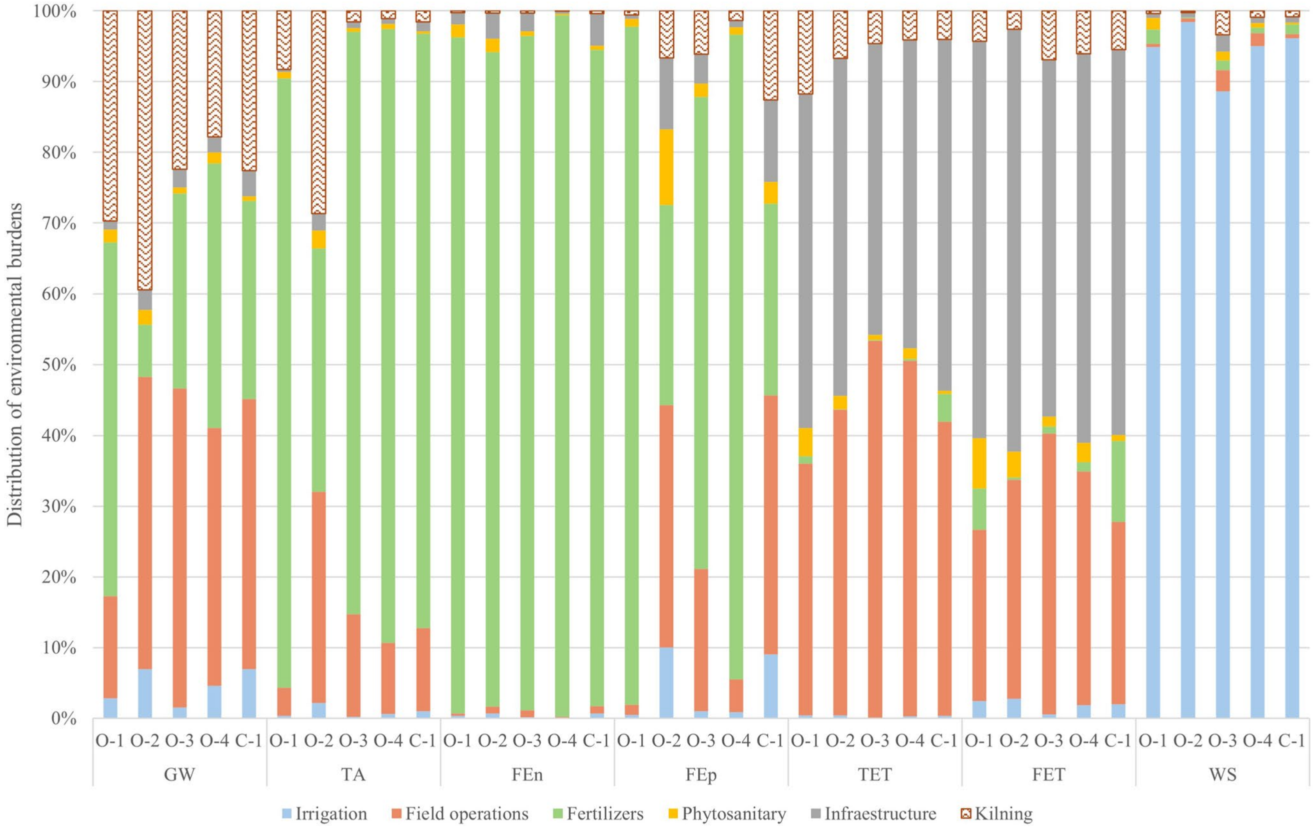


Fig. 4 Contribution analysis across production systems and impact categories. Acronyms: GW – global warming; TA – Terrestrial acidification; FEn – freshwater eutrophication, nitrogen related; FEp – freshwater eutrophication, phosphorus related; TET – Terrestrial ecotoxicity; FET – freshwater ecotoxicity; WS – water scarcity

Table 2 Resume of environmental results (per kg of dried hops)

FU: 1 kg of dried hops	GW kg CO_2eq	TA g SO_2 eq	FEn g N eq	FEp g P eq	FET kg 1,4-DCB	TET kg 1,4-DCB	WS m^3
Organic, medium yield	13.25	0.20	65.11	12.79	167.03	0.36	26.36
Organic, low yield	9.89	0.10	11.82	2.11	188.71	0.39	18.22
Conventional, low yield	10.64	0.14	11.73	1.38	240.80	0.55	39.48
Average ± standard deviation	11.26 ± 1.44	0.15 ± 0.04	29.55 ± 25.14	5.43 ± 5.22	198.85 ± 30.96	0.43 ± 0.08	28.02 ± 8.76

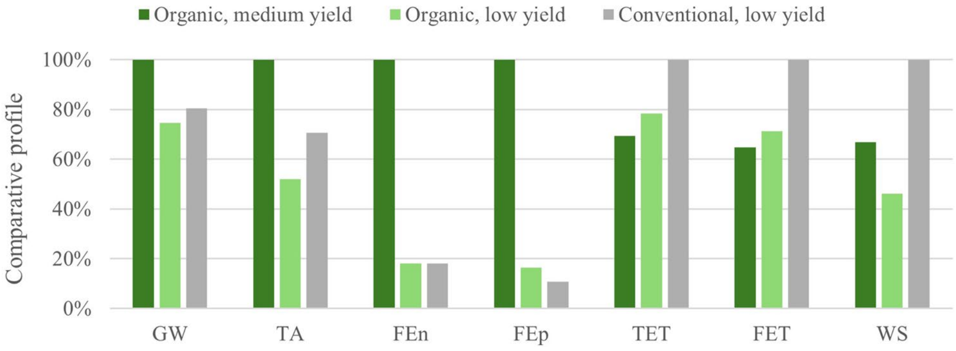


Fig. 5 Comparative environmental profile between hop production systems. Related to the FU. Acronyms: GW – global warming; TA – Terrestrial acidification; FEn – freshwater eutrophication, nitrogen related; FEp – freshwater eutrophication, phosphorus related; TET – Terrestrial ecotoxicity; FET – freshwater ecotoxicity; WS – water scarcity

NO_x. System O-2 diverges from this trend as a result of a reduced N input strategy, where emissions from combustion processes gain relative importance in the system's overall acidification profile.

For FEn, fertilizers are by far the dominant contributors across all systems, accounting for over 90% of the impact in each case, highlighting the critical role of nitrogen leaching from fertilization in freshwater eutrophication. Although fertilizers still account for most of the P-related eutrophication (e.g., 95% in O-4, 91% in O-1, 68% in O-3), the contribution from other sources such as field operations and infrastructure becomes more noticeable. P-related eutrophication can be more sensitive to other lifecycle stages, such as machinery use or infrastructure materials (e.g., steel production).

Typically, phytosanitary products such as pesticides, herbicides and fungicides are expected to be major contributors to ecotoxicity categories in agricultural systems. However, characterization profiles revealed a surprisingly low contribution from phytosanitary processes across all systems, contributing no more than 7% to FET and less than 4% to TET. Instead, the dominant contributions to TET and FET arise from field operations (machinery and diesel production) and infrastructure. Key contributors within infrastructure include the acquisition of creosote-treated wood, steel components, and to a lesser extent, coconut fibber ropes imported from South America. This outcome likely reflects the influence of stringent regulatory frameworks particularly the enforcement of maximum residue limits (EC 396/2005) which constrain both the frequency and intensity of pesticide applications.

WS serves as an indicator representing the relative available water remaining per area in a watershed, after the demand of humans and aquatic ecosystems has been met (Boulay et al. 2018). It assesses the potential of water deprivation, to either humans or ecosystems. As expected, it is fully dominated by irrigation in all systems (90–96%).

3.2 General comparison

A comparison was performed in terms of the FU. Because average yields vary widely among the systems (Table 1), they were grouped into three categories: O-1 and O-4 under an organic medium yield scenario; O-2 and O-3 under an organic low yield scenario; and C-1 under a conventional low yield scenario.

Table 2 and Fig. 5 summarize the environmental performance of the selected categories. Raw results for each production system can be consulted in Table SM 5 in the supplementary materials. Organic low yield systems stand out with the lowest impact in GW and TA categories primarily due to a reduced nitrogen input strategy. However, these systems showed moderately higher values for freshwater and terrestrial ecotoxicity compared to their high-yield counterparts. In contrast, organic high-yield systems, while maximizing productivity, are associated with significantly elevated freshwater eutrophication impacts, due to intensified nutrient inputs to sustain higher yields. Conventional low-yield systems present intermediate results for GW, TA and FE impacts, but demonstrate higher ecotoxicity and WS impacts.

Clear differences among practices are visibly represented in TA, TET, FET and WS, but especially for FEn and FEp. This limited divergence can be attributed to several interrelated factors: Yield levels are closely linked to fertilization intensity. A Spearman rank correlation analysis was performed to formally test the relationship between yield and fertilization intensity. A moderate positive association was observed between nitrogen input and yield (ρ = 0.60; *p* = 0.28). The association between phosphorus input and yield was weaker (ρ = 0.30; *p* = 0.62). Although statistical significance was limited due to the small sample size, the results suggest a tendency towards higher yields under higher nitrogen input levels. When analyzing categories nonrelated to fertilizer intensity like FET, TET or WS, organic systems result in less environmental impacts. However, in categories indirectly linked to fertilization, such as FE, GW or TA, differences became apparent, despite organic amendments typically having lower environmental burdens (as they come from organic residues). The greatest divergence was observed in freshwater eutrophication (FEn, FEp), where systems with higher fertilizer intensity showed disproportionately higher impacts, confirming that fertilization strategy is a dominant driver of environmental impact over all life cycle stages of hop production.

3.3 Sensitivity and uncertainty analysis

Fertilization was identified as a key hotspot in several impact categories; therefore, its influence was tested by conducting a parametric sensitivity analysis by changing the amount of fertilizer applied in each scenario by ±20% relative to the baseline. The variation was implemented in SimaPro® using parametrization sets. The sensitivity analysis revealed differentiated responses across impact categories (Fig. 6).

GW showed limited sensitivity to fertilizer variation with changes ranging from less than 1% (O-2) to about 6% (O-1). TA exhibited a stronger response, with impacts varying by approximately ±8–17%, reflecting the important contribution of fertilizer-related emissions, particularly NH_3 volatilization. The highest sensibility was observed for FEn, showing almost a proportional response, with changes close to ±18–20% across all systems, as expected. FEp showed a more heterogeneous response. Impacts varied by approximately ±18–19% in systems O-1 and O-4, ±12% in O-3, and around ±6% in O-2 and C-1 suggesting a greater contribution from non-fertilizer-related processes. Changes in the remaining impact categories (TET, FET and WS) were below 1% across all systems and are therefore not discussed further.

Data uncertainty was assessed performing a Monte Carlo simulation (up to 250 iterations). Results of the uncertainty analysis for the elected impact categories are reported in Supplementary Materials (Table SM 6).

4 Discussion

4.1 Carbon footprint comparison with previous studies

Hauser (2019) calculated the carbon footprint of hop production using existing literature and industry data from hop farms in the US Pacific Northwest (the region accounting for most of the American hop production in 2017). Under the scope, they included agricultural machinery, irrigation, fertilizers, soil emissions, pesticides, and kilning. However, infrastructure related to the trellis system was not included or specified. They reported a carbon footprint of 3.5 to 5.5 kg CO_2eq per kg of hop pellet, values consistent with additional unpublished estimates for U.S. aroma hops: 4.1–5.1 kg CO_2eq/kg (Bristol 2022). The values achieved in the present study double (and in some cases nearly triple), besides having a very similar share of emissions attributed to processes such as machinery and kilning (Table 3). This substantial difference is closely linked to lower yields in French systems (between 500 and 1200 kg/ha) compared to those in Oregon and Washington (around 2200 kg/ha). Yield is a critical factor. In new hop growing areas of France, farms have not achieved yields high enough to offset the

Fig. 6 Sensitivity analysis. Results of each scenario are normalized to the base line (100%)

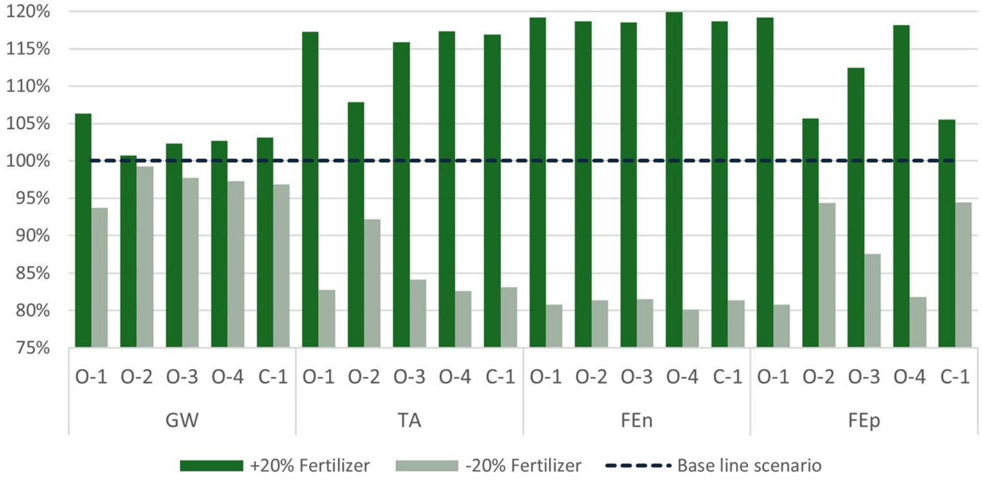


Table 3 Absolute emissions (kg CO_2eq per kg hop) and percentage of contribution of each emission source based on a cradle-to-farm-gate scope. For US (Hauser 2019) and French hop production systems

Emission Source (GW)	U.S. (high yield) (kg CO_2eq/kg hop)	%(US)	France (low to mid yield) (kg CO_2eq/kg hop)	% (France)
Kilning	1.7	31–48%	1.8–5.2	18–39%
Field operations	0.5–2.0	10–42%	1.4–6.0	14–45%
Fertilizer production	0.3–1.2	5–22%	0.7–6.7	7–50%
Irrigation	0.5	9–14%	0.2–0.9	2–7%
Soil emissions	0.1–0.4	2–7%	0.5–2.0	5–15%
Pesticides	0.05–1.1	1–20%	<0.9	<7%
Infrastructure	-	-	<0.5	1–4%
Total GW	3.5–5.5	100%	9.9–13.3	100%

increased environmental burden. A key contributing factor is the limited agronomic expertise among growers, particularly within organic systems. In contrast, constant inputs and regional yields were assumed for the well stablished US fields; for example, assuming 140 kg N/ha across yield levels. While this assumption is within the recommended nitrogen application range for hops in the US Pacific Northwest (112–168 kg N/ha) (Sullivan et al. 1999) it may underestimate true fertilizer use at high productivity levels. Also, while they considered only one year of production, we considered a 20-year approach, with a yield progression, and including infrastructure installation and dismantling. Considering these assumptions, our results for GW remain within the same order of magnitude, suggesting that yield difference due to optimized growing techniques is the key driver of the observed variation.

Due to the lack of published LCAs on hop production with a comparable scope, direct benchmarking with other impact categories was not possible.

4.2 Addressing spatial variability in leaching models

Several approaches have been developed to estimate nutrient leaching in agroecosystems, varying in complexity, data requirements and spatial accuracy. One of the most widely used methods in agricultural LCA studies is the IPCC (2021) approach (Tier I), which applies a fixed emission factor per kg of nitrogen applied, with the objective of estimating the fraction leached as nitrate that may subsequently contribute to induced N_2O emissions. While this method is simple and easily applicable in national inventories, it lacks the ability to reflect spatial and temporal variability in soil-climate conditions and site-specific management practices. More refined, Tier II models such as SALCA-Nitrate or SALCA-P (Nemecek et al. 2024) and the SQCB-NO_3 model (Ziep et al. 2009) incorporate agroclimatic variables, crop rotations, and soil characteristics, offering more realistic nitrate and phosphate runoff estimations. However, their use is often limited by regional specificity (e.g., SALCA's calibration for alpine environments) or by the need for detailed input data that may not be available at larger scales. In this context, the NDR model from the InVEST suite represents a robust and scalable alternative, that explicitly simulates the spatial transport of nutrients from source areas to receiving water bodies, considering biophysical factors (e.g., slope, vegetation cover, land use), local climate (e.g. monthly precipitation and evapotranspiration) and hydrological conditions (e.g. quick run-off, river network) all obtained from open sources (see SM section B). The comparison of nitrogen leaching estimates among three approaches (Fig. 7) further illustrates these methodological differences. The IPCC (2021) Tier I approach produced linear, proportional results relative to the initial nitrogen load, reflecting its simplified and generic emission factor structure. In contrast, the SCBQ Tier II model reported intermediate values and showed greater sensitivity to soil characteristics, particularly lower clay contents, which enhance nitrate mobility. The spatially explicit NDR (InVEST) model yielded the most conservative overall results, showing a stepped progression across farms with a notable exception at O-4, where estimated exports were considerably higher. This outlier corresponds to a farm bordering a river (*Le Mondot*), highlighting the model's responsiveness to hydrological connectivity and its ability to capture nutrient losses in fields located near watercourses. These findings confirm that GIS-based models can reflect site-specific risks of nutrient contamination and therefore complement traditional Tier I–II approaches within agricultural LCA frameworks.

4.3 Implications for sustainable hop production

Maximizing yield while optimizing fertilizer inputs appears to be the most effective strategy for minimizing environmental impacts in hop production systems. This requires balancing nutrient inputs within crop needs, confirming the need for soil testing and site-specific fertilization strategies. Requirements vary depending on soil characteristics and growing region (Rossini et al. 2021). Indications go from 130 to 170 kg/ha for N in temperate climates (Senske et al. 2020) and 100–150 kg/ha in Mediterranean regions (Potopová et al. 2021). Guidelines also indicate that P fertilization is often overestimated. Hops typically have low P requirements, with suggested P amount to be applied ranging from 67 to 110 kg/ha, when soil P concentration into the soil is very low (0–30 ppm, Senske et al. 2020). These practices could help reduce diffuse N and P losses, thus minimizing impacts in key categories such as GW, TA and FE.

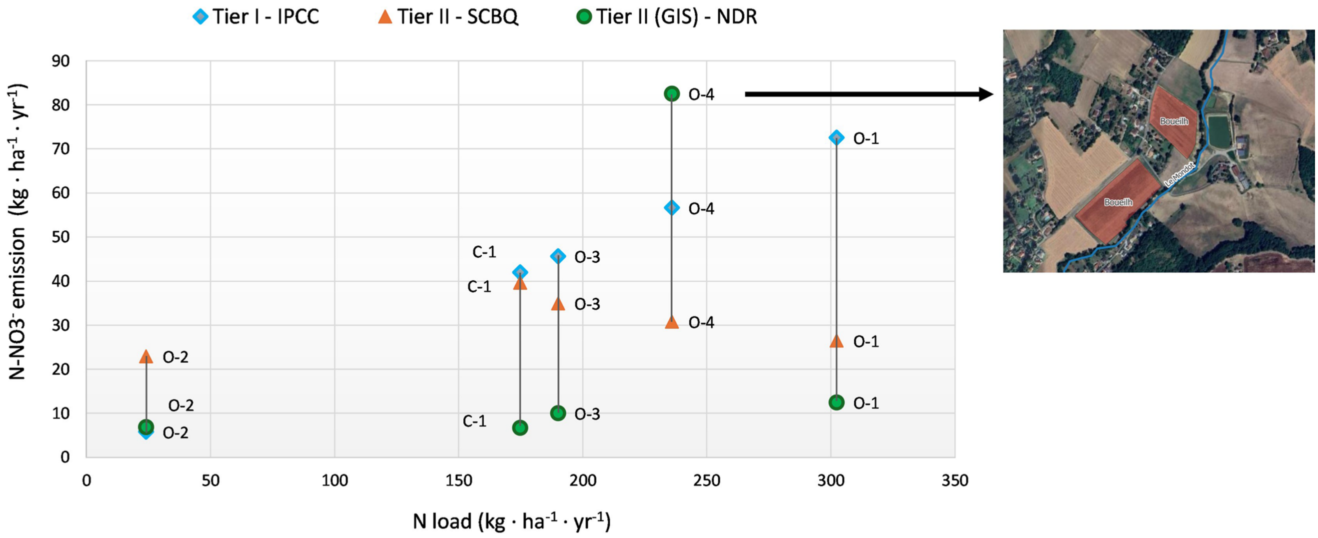


Fig. 7 Estimated nitrate loads reaching water bodies as predicted by three emission modeling approaches (Tier I – IPCC, Tier II – SCBQ, and Tier II – NDR) for the systems under study. O-4 scenario showed higher expected nitrate emissions due to river connection with fields

Also, alternative ways to improve soil fertility have been proposed such as the localized application of fertilizers or, even better, the use of fertigation systems (Delahunty and Johnston 2014; Rossini et al. 2021). Drip fertigation can reduce all major N-loss pathways (NH_3, N_2O, NO_3^- leaching) compared to broadcast application of slurry liquid fraction (Zheng et al. 2023; Zhu et al. 2023; Capra et al. 2025). Given the high N demands of hops and the limitations of organic fertilizers, integrating drip fertigation could significantly improve nutrient use efficiency, maintain high yields, and reduce fuel consumption related to the use of agricultural machinery. Moreover, fertigation could also have co-benefits by applying reclaimed water (i.e. treated wastewater suitable for agricultural purposes) reducing impacts on climate change and freshwater consumption (Hospido et al. 2013; Canaj et al. 2021; Nadeem et al. 2024).

Finally, despite the growing interest in the application of plant biostimulants in other crops, studies for hops are very scarce (Procházka et al. 2018). Still, some experiments showed great results by applying a mixture of biostimulants composed of humic and fulvic acids which increased yields at a range of 0.40–0.49 t dried hop cones·ha^{-1}. However, future studies comparing mineral and organic fertilizers with biostimulants should consider upstream processes associated with the production and acquisition of the latter.

4.4 Implications for the beer supply chain

On a per-kilogram basis, hop cultivation has a relatively high environmental burden than other beer ingredients such as barley or wheat (Dijkman et al. 2017; Tricase et al. 2018; Câmara-Salim et al. 2020). However, the amount of hops used for instance in lager beers is typically very low. For example, the revised Product Environmental Footprint Category Rules (PEFCR) for Beer (European Commission 2025) assumes hop additions in the range of 0.2–0.4 g/L for most beer styles. Under this assumption, the environmental contribution of hops is considered negligible (less than 1%) (Table 4). In contrast, craft breweries declare to use between 4 and 16 g/L of hops in highly hopped styles such as Pale Ales (Lafontaine and Shellhammer 2018). At these levels, the contribution of hops becomes increasingly significant (Table 4), potentially accounting for up to a third of the total cradle-to-gate GHG emissions per liter of beer when assuming 0.5 kg CO_2eq per liter of beer on a cradle to brewery-gate approach (D'Ascenzo et al. 2024; European Commission 2025).

Table 4 Estimated potential carbon footprint contribution of hops per liter of beer. Assuming a range of 5.5–11.3 kgCO_2eq/kg hop

Hop use (g/L)	Hop emissions (g CO₂eq/L)	% of carbon footprint in beer
0.2	1.1–2.3	0.2% − 0.5%
3	16.5–33.9	3.3–6.8%
4	22.0–45.2	4.4–9.0%
8	44.0–90.4	8.8–18.1%
16	88.0–180.8	17.6–36.2%

Nonetheless, from a sensory and aromatic perspective, Lafontaine and Shellhammer (2018) found that concentrations within the 4–8 g/L range are considered optimal for achieving desirable hop aroma characteristics, with saturation occurring beyond 8 g/L, yielding limited additional perceptual benefits. Consequently, in such styles, the carbon footprint associated with hop use may account for a substantially larger proportion of the total beer footprint, challenging current LCA assumptions and highlighting the need for differentiated environmental assessments across beer typologies.

4.5 Limitations and future opportunities

Some limitations should be acknowledged. First, the analysis is based on a limited number of hop farms located in an emerging hop-growing region. Production in newly established regions is often characterized by considerable variability in farmers' expertise. Consequently, our results should be interpreted as indicative of current practices within this specific context rather than representative of the entire French hop sector. Although the selected scenarios capture relevant variability in management strategies, the limited sample size restricts statistical representativeness of the results, for example regarding fertilization intensity and yield progression. Also, available data for the perennial nature of hop cultivation required simplifying assumptions regarding long-term crop dynamics. The productive cycle was represented over a 20-year lifespan using a yield progression derived from literature, based on an initial four-year of real yield data. However, under this approach, potential variations of crop demands (e.g. fertilizer or phytosanitary demands, and derived emissions) don't change over time. Future studies could address these aspects by incorporating dynamic modelling approaches or longer series of farm data.

It is also important to consider the uncertainties associated with the use of the NDR model as a predictive tool. Modeling of the watershed scale dynamics is challenging (Breuer et al. 2008) and the NDR model includes relatively limited number of the wide range of complex processes that influence nutrient transport from land to watercourses (see reviews in Edwards and Withers 2008; Pärn et al. 2012). A review on the limitations of the NDR model was conducted by Redhead et al. (2018) concluding that whilst it gives good estimates of the relative magnitude of nutrient exports across catchments, absolute values are frequently underestimated.

More broadly, the integration of GIS-based models within LCA framework also presents methodological challenges. Spatial models often require high-resolution environmental data and site-specific parameters, which may not always be available or easily transferable across regions. This can limit the scalability and reproducibility of GIS–LCA approaches when applied to larger geographical scales or different pedoclimatic contexts. At the same time, the integration of spatial modelling tools represents a promising avenue for improving the representation of site-specific processes in agricultural LCA, particularly for nutrient transport, water use and other landscape-dependent impacts. Developing standardized workflows and harmonized datasets could facilitate the wider adoption and scalability of GIS–LCA approaches in future environmental assessments.

Despite these limitations, the study also highlights opportunities for further research on environmental assessment of hop production. Future work should focus on addressing performance at more well-established hop-producing regions, for example in Germany or the US; as they are the biggest producers globally, it would improve the representativeness of the hop footprint. Moreover, developing detailed assessments for aroma and alpha hops would allow for the evaluation of how brewing recipes influence the overall environmental footprint of different beer types.

5 Conclusions

This study assessed the environmental profile of different hop production systems in a new hop growing region in France. Foreground data were improved by applying a spatially explicit model for nutrient leaching, demonstrating that GIS can be applied in the LCA framework as medium complexity models accounting for spatial variability with a moderate need for data and modeling expertise. By doing so, its added value for regionalized assessments has been demonstrated.

Carbon footprint, primarily driven by emissions associated with fertilization and energy use, was found to be double on average than the U.S. systems, mainly because of low yields. Therefore, enhancing the sustainability of hop cultivation in France, in new growing areas, requires increasing yields, while optimizing fertilizer doses and delivery techniques. Integrating carbon footprint reduction strategies, such as precision agriculture, renewable energy sources, and low-emission fertilizers, will be essential to align hop production with climate change mitigation goals. Notably, both organic and conventional hop production in France exhibited low ecotoxicity impacts related to phytosanitary product use, which is a positive outcome in the context of pesticide management, but it revealed the need for including infrastructure and machinery production under the scope of agricultural LCAs.

Overall results indicate that hop cultivation exhibits relatively high environmental burdens compared to other beer ingredients such as barley or wheat. While its contribution may be minimal in traditional lager styles (which still dominate the global beer market) this impact becomes significantly more relevant in high-hopped beer styles, particularly within the growing craft beer segment. As the beer market diversifies and expands to include a wider range of intensely hopped varieties, the environmental footprint of hops can no longer be overlooked.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-026-02651-y.

Acknowledgements This work has been partially supported by the project has been partially supported by the project CÓMBARO, which is being developed under the aid called by the Galician Food Quality Agency (Agacal) in 2023 for the execution of innovative projects of the operational groups of the European Innovation Association (EIP-Agri), co-financed with the European Agricultural Fund for Rural Development (EAFRD 2023/052) within the framework of the Strategic Plan of the Common Agricultural Policy (PEPAC) 2023-2027, and by the project *"Sustainable management of water resources in irrigated agriculture in the SUDOE area (I-ReWater-S1/2.5/E0136)"*, co-funded by the program INTERREG SUDOE, and by the *NUTRITIVE* project (Grant agreement No. 10113540), funded by the European Commission HORIZON-CL6–2023-ZEROPOLLUTION-02. A.F., A.A., A.H. and S.G.G. belong to the Galician Competitive Research Group (GRC ED431C 2021/37) and to the Cross-disciplinary Research in Environmental Technologies (CRETUS Research Center, ED431G/2023/12), program co-funded by FEDER (UE). HOPEN is also acknowledged for providing farmers' data.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Data availability The data supporting the findings of this study are available in Supplementary Materials, Section A, Tables SM1 and SM2.

Declarations

Declaration of generative AI in scientific writing During the preparation of this work the author(s) used CHAT GPT to assist with language refinement and style. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Adewale C, Reganold JP, Higgins S, Evans RD, Carpenter-Boggs L (2018) Improving carbon footprinting of agricultural systems: boundaries, tiers, and organic farming. Environ Impact Assess Rev 71:41–48. https://doi.org/10.1016/j.eiar.2018.04.004

Alhashim R, Deepa R, Anandhi A (2021) Environmental impact assessment of agricultural production using LCA: a review. Climate 9(11):164. https://doi.org/10.3390/cli9110164

Almaguer C, Schönberger C, Gastl M et al (2014) Humulus lupulus - a story that begs to be told. A review. J Inst Brew n/a-n/a. https://doi.org/10.1002/jib.160

Amienyo D, Azapagic A (2016) Life cycle environmental impacts and costs of beer production and consumption in the UK. Int J Life Cycle Assess 21(4):492–509. https://doi.org/10.1007/s11367-016-1028-6

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

Bessou C, Basset-Mens C, Tran T, Benoist A (2013) LCA applied to perennial cropping systems: a review focused on the farm stage. Int J Life Cycle Assess 18(2):340–361. https://doi.org/10.1007/s11367-012-0502-z

Beverage Industry Environmental Roundtable (2012) Research on the carbon footprint of beer

BH (2024) Barthhaas report 2023/2024

Blonk Consultants (2022) Agri-footprint 6 methodology report

Boulay A-M, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess 23(2):368–378. https://doi.org/10.1007/s11367-017-1333-8

Breuer L, Vaché KB, Julich S, Frede H-G (2008) Current concepts in nitrogen dynamics for mesoscale catchments. Hydrological Sci J 53(5):1059–1074. https://doi.org/10.1623/hysj.53.5.1059

Bristol C (2022) A cradle-to-gate Life cycle assessment of American hops in the craft beer supply chain. Faculty of California Polytechnic State University, San Luis Obispo. College of Agriculture, Food, and Environmental Sciences

Bulle C, Margni M, Patouillard L, Boulay A-M, Bourgault G, De Bruille V, Cao V, Hauschild M, Henderson A, Humbert S, Kashef-Haghighi S, Kounina A, Laurent A, Levasseur A, Liard G, Rosenbaum RK, Roy P-O, Shaked S, Fantke P, Jolliet O (2019) IMPACT World+: a globally regionalized life cycle impact assessment method. Int J Life Cycle Assess 24(9):1653–1674. https://doi.org/10.1007/s11367-019-01583-0

Cabras I, K DF, D RB, Higgins D (2023) Beer, brewing, and regional studies. Reg Stud 57(10):1905–1908. https://doi.org/10.1080/00343404.2023.2216066

Câmara-Salim I, Almeida-García F, González-García S, Romero-Rodríguez A, Ruíz-Nogueiras B, Pereira-Lorenzo S, Feijoo G, Moreira MT (2020) Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain. Sci Total Environ 713:136720. https://doi.org/10.1016/j.scitotenv.2020.136720

Canaj K, Morrone D, Roma R, Boari F, Cantore V, Todorovic M (2021) Reclaimed water for vineyard irrigation in a Mediterranean context: life cycle environmental impacts, Life cycle costs, and eco-efficiency. Water (Basel) 13(16):2242. https://doi.org/10.3390/w13162242

Capra F, Ardenti F, Abalos D, Lommi M, Pochintesta D, Ganugi P, Perego A, Tabaglio V, Fiorini A (2025) Drip fertigation with slurry as a promising tool to reduce nitrogen losses under organic maize. Sci Rep 15(1):16890. https://doi.org/10.1038/s41598-025-01487-0

Chaplin-Kramer R, Sim S, Hamel P, Bryant B, Noe R, Mueller C, Rigarlsford G, Kulak M, Kowal V, Sharp R, Clavreul J, Price E, Polasky S, Ruckelshaus M, Daily G (2017) Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. Nat Commun 8(1):15065. https://doi.org/10.1038/ncomms15065

Cinardi G, D'Urso PR, Arcidiacono C, Muradin M, Ingrao C (2025) A systematic literature review of environmental assessments of citrus processing systems, with a focus on the drying phase. Sci Total Environ 974:179219. https://doi.org/10.1016/j.scitotenv.2025.179219

Clark M, Tilman D (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett 12(6):064016. https://doi.org/10.1088/1748-9326/aa6cd5

The Climate Data (2025) Aquitaine climate. https://en.climate-data.org/europe/france/aquitaine-291/. 10 Mar 2026

Coulon S (2024) Regards croisés: producing hops in the grand ouest region. In Conference at SIVAL. https://www.sival-angers.com/en/article/regards-croises-produire-du-houblon-dans-le-grand-ouest. 6 May 2025

D'Ascenzo F, Vinci G, Maddaloni L, Ruggeri M, Savastano M (2024) Application of Life cycle assessment in beer production: systematic review. Beverages 10(3):86. https://doi.org/10.3390/beverages10030086

Delahunty K, Johnston J (2014) 2014 USDA Northeast SARE final report: investigating best practices for timing and amount of organic soluble nitrate fertigation of hops in the Northeast. Westfield, Maine

Dighe RS (2017) The craft beer explosion: why here? Why Now? process: a blog for American history

Dijkman TJ, Birkved M, Saxe H, Wenzel H, Hauschild MZ (2017) Environmental impacts of barley cultivation under current and future climatic conditions. J Cleaner Prod 140:644–653. https://doi.org/10.1016/j.jclepro.2016.05.154

EC (2005) Council Regulation No 396/2005 of the European Parliament and of the Council of 23 February 2005 on maximum residue levels of pesticides in or on food and feed of plant and animal origin and amending Council directive 91/414/EEC text with EEA relevance

EC (2007) Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91

Ecoinvent. (2023) ecoinvent database 3.10

Edwards AC, Withers PJA (2008) Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the Uk. J Hydrol 350(3–4):144–153. https://doi.org/10.1016/j.jhydrol.2007.10.053

Elsaholi M, Kelly-Quinn M (2013) The effect of nutrient concentrations and ratios on periphyton biomass in low conductivity streams: implications for determination of nutrient limitation. IW 3(4):451–458. https://doi.org/10.5268/IW-3.4.595

EMEP/EEA (2023) Air pollutant emission inventory guidebook 2023. 3.D crop production and agricultural soils

European Commission (2017) PEFCR Guidance document, - Guidance for the 13 development of product environmental footprint Category Rules (PEFCRs), version 6.3

European Commission (2025) Revised PEFCR for beer

FAO (2021) The state of the world's land and water resources for food and agriculture - systems at breaking point. Synthesis report 2021

González A, Gilmer A, Foley R, Sweeney J, Fry J (2011) Applying geographic information systems to support strategic environmental assessment: opportunities and limitations in the context of Irish land-use plans. Environ Impact Assess Rev 31(3):368–381. https://doi.org/10.1016/j.eiar.2010.12.001

Gribbins (2025) The year in craft beer: growth slows, strategy shifts but success still brews. Craft Brew Bus

Grieco R, Belfiore OR, Cervelli E, Bovo M, Pindozzi S, Scotto di Perta E, Tassinari P, Torreggiani D (2025) Identification, assessment and management of nitrogen load hotspots from livestock farming: comparative analysis using regional land-use data and ESA world cover product. Comput Electron Agric 236:110474. https://doi.org/10.1016/j.compag.2025.110474

Grieco R, Cervelli E, Bovo M, Pindozzi S, Scotto di Perta E, Tassinari P, Torreggiani D (2024) The role of geospatial technologies for sustainable livestock manure management: a systematic review. Sci Total Environ 954:176687. https://doi.org/10.1016/j.scitotenv.2024.176687

Hauser S (2019) An overview of Sustainability Challenges in beer production, and the carbon footprint of hops production. Department of Food Science and Technology, Oregon State University. Master Brewers Association of the Americas 56. https://doi.org/10.1094/TQ-56-4-0731-01

Hospido A, Núñez M, Antón A (2013) Irrigation mix: how to include water sources when assessing freshwater consumption impacts associated to crops. Int J Life Cycle Assess 18(4):881–890. https://doi.org/10.1007/s11367-012-0523-7

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y

IPCC (2019a) 2019 refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In: Chapter, vol 10. Emissions from Livestock and Manure Management

IPCC (2019b) 2019 refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter, 11: n_2O emissions from managed soils, and CO_2 Emissions from Lime and Urea Application

IPCC. Intergovernmental Panel for Climate Change, Arias PA, Bellouin N et al (2021) Technical summary. In climate change, 2021: the Physical Science Basis. Contribution of working group I to the sixth assessment report of the intergovernmental Panel on climate change. In: Climate change 2021 - the physical science basis. Cambridge University Press, pp 33–144

ISO (2021a) Environmental management - Life cycle assessment: principles and framework. ISO 14040. https://doi.org/2006/A1:2021

ISO (2021b) Environmental management - Life cycle assessment: requirements and Guidelines. ISO 14044. https://doi.org/2006/A2:2021

Kaita MS, Harun SN (2023) Application of integrated LCA-GIS model in the agricultural sector: a brief overview. IOP Conf Ser Earth Environ Sci 1167(1):012015. https://doi.org/10.1088/1755-1315/1167/1/012015

Klimczak K, Cioch-Skoneczny M, Duda-Chodak A (2023) Effects of dry-hopping on beer chemistry and sensory properties—A review. Molecules 28(18):6648. https://doi.org/10.3390/molecules28186648

Knuchel R, Gaillard G, Roches A et al (2009) How to cope best with field emissions of nitrate in a food LCA. In Int. Conference on Life Cycle Management, Capetown

Lafontaine SR, Shellhammer TH (2018) Impact of static dry-hopping rate on the sensory and analytical profiles of beer. J Inst Brew 124(4):434–442. https://doi.org/10.1002/jib.517

Lee EK, Zhang X, Adler PR, Kleppel GS, Romeiko XX (2020) Spatially and temporally explicit life cycle global warming, eutrophication, and acidification impacts from corn production in the U.S. Midwest. J Cleaner Prod 242:118465. https://doi.org/10.1016/j.jclepro.2019.118465

Liu Q, Qiao N, Xu X, Xin X, Han JY, Tian Y, Ouyang H, Kuzyakov Y (2016) Nitrogen acquisition by plants and microorganisms in a temperate grassland. Sci Rep 6(1):22642. https://doi.org/10.1038/srep22642

Magadán O, P et al (2011) Guía del cultivo del lúpulo

Mattila T, Helin T, Antikainen R (2012) Land use indicators in life cycle assessment. Int J Life Cycle Assess 17(3):277–286. https://doi.org/10.1007/s11367-011-0353-z

McDonagh K, Zhang R, Merkouri L-P, Arnell M, Hepworth A, Duyar M, Short M (2024) Lowering the carbon footprint of beer through waste breadcrumb substitution for malted barley: life cycle assessment and experimental study. Cleaner Environ Syst 15:100241. https://doi.org/10.1016/j.cesys.2024.100241

Nadeem A, Tariq MAUR, Sarwar K, Iqbal M, Ahmad K, Ahmed K (2024) Assessing the environmental impacts of reclaimed and conventional water in hydroponics based on a life cycle assessment approach. Water Supply 24(8):2765–2780. https://doi.org/10.2166/ws.2024.160

Natural Capital Project (2024) InVEST 3.14.3 User's Guide. Stanford University, University of Minnesota

Nemecek T, Roesch A, Bystricky M, Jeanneret P, Lansche J, Stüssi M, Gaillard G (2024) Swiss agricultural Life cycle assessment: a method to assess the emissions and environmental impacts of agricultural systems and products. Int J Life Cycle Assess 29(3):433–455. https://doi.org/10.1007/s11367-023-02255-w

OECD (2023) Health at a glance, 2023: OECD Indicators. París

Oladokun O, James S, Cowley T et al (2017) Dry-hopping: the Effects of temperature and hop variety on the bittering profiles and properties of resultant beers. Brew Sci 70:187–196. https://doi.org/10.23763/BrSc17-18oladokun

Pan B, Lam SK, Mosier A, Luo Y, Chen D (2016) Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. Agr Ecosyst Environ 232:283–289. https://doi.org/10.1016/j.agee.2016.08.019

Pärn J, Pinay G, Mander Ü (2012) Indicators of nutrients transport from agricultural catchments under temperate climate: a review. Ecol Indic 22:4–15. https://doi.org/10.1016/j.ecolind.2011.10.002

Payen S, Cosme N, Elliott AH (2021) Freshwater eutrophication: spatially explicit fate factors for nitrogen and phosphorus emissions at the global scale. Int J Life Cycle Assess 26(2):388–401. https://doi.org/10.1007/s11367-020-01847-0

Pfister S, Oberschelp C, Sonderegger T (2020) Regionalized LCA in practice: the need for a universal shapefile to match LCI and LCIA. Int J Life Cycle Assess 25(10):1867–1871. https://doi.org/10.1007/s11367-020-01816-7

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360(6392):987–992. https://doi.org/10.1126/science.aaq0216

Potopová V, Lhotka O, Možný M, Musiolková M (2021) Vulnerability of hop-yields due to compound drought and heat events over European key-hop regions. Intl J Climatol 41(S1). https://doi.org/10.1002/joc.6836

PRé Sustainability (2022) Simapro database manual. Methods library

Procházka P, Štranc P, Pazderu K, Vostřel J, Řehoř J (2018) Use of biologically active substances in hops. Plant Soil Environ 64(12):626–632. https://doi.org/10.17221/655/2018-PSE

Redhead JW, May L, Oliver TH, Hamel P, Sharp R, Bullock JM (2018) National scale evaluation of the InVEST nutrient retention model in the United Kingdom. Sci Total Environ 610-611:666–677. https://doi.org/10.1016/j.scitotenv.2017.08.092

Rossini F, Virga G, Loreti P, Iacuzzi N, Ruggeri R, Provenzano ME (2021) Hops (Humulus lupulus L.) as a novel multipurpose crop for the Mediterranean region of Europe: challenges and opportunities of their cultivation. Agriculture 11(6):484. https://doi.org/10.3390/agriculture11060484

Ruggeri R, Rossini F, Roberto SR, Sato AJ, Loussert P, Rutto LK, Agehara S (2024) Development of hop cultivation in new growing areas: the state of the art and the way forward. Eur J Agron 161:127335. https://doi.org/10.1016/j.eja.2024.127335

Saget S, Porto Costa M, Black K, Iannetta PPM, Reckling M, Styles D, Williams M (2022) Environmental impacts of Scottish faba bean-based beer in an integrated beer and animal feed value chain. Sustain Prod Consumption 34:330–341. https://doi.org/10.1016/j.spc.2022.09.019

Senske A, Dixon P, Hodgson E, Thoms A (2020) Optimization of N fertilization for hops (Humulus lupulus) in Iowa soils. Ames, Iowa

Shi S, Yan X (2024) A critical review on spatially explicit life cycle assessment methodologies and applications. Sustain Prod Consumption 52:566–579. https://doi.org/10.1016/j.spc.2024.11.015

Singh S, Singh R, Singh K, Katoch K, Zaeen AA, Birhan DA, Singh A, Sandhu HS, Singh H, Sahrma LK (2024) Smart fertilizer technologies: an environmental impact assessment for sustainable agriculture. Smart Agric Technol 8:100504. https://doi.org/10.1016/j.atech.2024.100504

Sipperly E, Ziegler R (2014) Comparative cradle to gate Life cycle assessment of 100% barley-based singha Lager beer in Thailand. Bangkok

Sullivan D, Hart J, Christensen N (1999) Nitrogen uptake and utilization by Pacific Northwest crops

Thoma G, Tichenor Blackstone N, Nemecek T, Jolliet O (2022) Life cycle assessment of food systems and diets. In: Food systems modelling. Elsevier, pp 37–62

Tricase C, Lamonaca E, Ingrao C, Bacenetti J, Lo Giudice A (2018) A comparative Life cycle assessment between organic and conventional barley cultivation for sustainable agriculture pathways. J Cleaner Prod 172:3747–3759. https://doi.org/10.1016/j.jclepro.2017.07.008

Verones F, Hellweg S, Antón A, Azevedo LB, Chaudhary A, Cosme N, Cucurachi S, de Baan L, Dong Y, Fantke P, Golsteijn L, Hauschild M, Heijungs R, Jolliet O, Juraske R, Larsen H, Laurent A, Mutel CL, Margni M, Núñez M, Owsianiak M, Pfister S, Ponsioen T, Preiss P, Rosenbaum RK, Roy P-O, Sala S, Steinmann Z, van Zelm R, Van Dingenen R, Vieira M, Huijbregts MAJ (2020) LC-IMPACT: a regionalized life cycle damage assessment method. J Ind Ecol 24(6):1201–1219. https://doi.org/10.1111/jiec.13018

Wowra K, Zeller V, Schebek L (2021) Nitrogen in Life cycle assessment (LCA) of agricultural crop production systems: comparative analysis of regionalization approaches. Sci Total Environ 763:143009. https://doi.org/10.1016/j.scitotenv.2020.143009

Yang C (2022) Review on the causes of eutrophication in water 246–252. https://doi.org/10.2991/978-2-494069-31-2_30

Zheng J, Zhou M, Zhu B, Fan J, Lin H, Ren B, Zhang F (2023) Drip fertigation sustains crop productivity while mitigating reactive nitrogen losses in Chinese agricultural systems: evidence from a meta-analysis. Sci Total Environ 886:163804. https://doi.org/10.1016/j.scitotenv.2023.163804

Zhou J, Han X, Brookes JD, Qin B (2022) High probability of nitrogen and phosphorus co-limitation occurring in eutrophic lakes. Environ Pollut 292:118276. https://doi.org/10.1016/j.envpol.2021.118276

Zhu Y, Zhang H, Li R, Zhu W, Kang Y (2023) Nitrogen fertigation affects crop yield, nitrogen loss and gaseous emissions: a meta-analysis. Nutr Cycl Agroecosyst 127(3):359–373. https://doi.org/10.1007/s10705-023-10318-5

Ziep T, Wohlgemuth V, Emmenegger MF et al (2009) SQCB - Sustainability quick check tool for biofuels 189–202