

ORIGINAL ARTICLE

Special Section: Advances in On-Farm Agronomic Research and Participatory Learning

On-farm observations of socioenvironmental impacts of *Humulus lupulus* L. cultivation in Brazil

Viviany Viriato^{1,2}  | Geraldo Stachetti Rodrigues³  | Marcio Renato Nunes²  |
Abebe Belay Adege²  | Filipe Pereira Giardini Bonfim¹ 

¹Departamento de Produção Vegetal, Setor de Horticultura, Faculdade de Ciências Agrônomicas, Universidade Estadual Paulista (Unesp), Botucatu, São Paulo, Brazil

²Soil, Water, and Ecosystem Sciences Department, Global Food System Institute, University of Florida/IFAS, Gainesville, Florida, USA

³Laboratório de Gestão Ambiental, Embrapa Meio Ambiente, Jaguariúna, São Paulo, Brazil

Correspondence

Viviany Viriato and Filipe Pereira Giardini Bonfim, Departamento de Produção Vegetal, Setor de Horticultura, Faculdade de Ciências Agrônomicas, Universidade Estadual Paulista (Unesp), Botucatu, Av. Universitária, 3780, Altos do Paraíso, 18610-034, SP, Brazil.
Email: viviany.viriato@unesp.br and filipe.giardini@unesp.br

Assigned to Associate Editor David Suchoff.

Funding information

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES), Grant/Award Number: 001; Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil, Grant/Award Number: 2023/12485-0

Abstract

Hops (*Humulus lupulus* L.) have been cultivated in Brazil, the world's third-largest beer producer, to meet the growing demand of its expanding brewing industry. Despite advances in agricultural practices, research on the sustainability of tropicalizing hop production remains limited. This study evaluates the social and environmental impacts of hop production in 10 reference farms across the Brazilian states of Alagoas, Goiás, and São Paulo using the Ambitec-Agro tool. This tool assesses the impacts generated by technological innovations adopted in rural environments through change coefficients incorporated into multicriteria indicators, with weights assigned based on the spatial scale of impact occurrence within the farms. Impact indices were calculated across seven aspects: technology efficiency, environmental quality, customer respect, employment, income, health, and management and governance. These aspects were integrated into 27 criteria and 148 indicators. The results indicate positive outcomes across most criteria, with occasional temporary negative results related to energy consumption; use of agricultural inputs and raw materials; water consumption; occupational safety and health; and atmospheric emissions. To address these issues, farmers have invested in solar panels to reduce energy consumption and support other crops, implemented fertigation to improve water and input efficiency, promoted the safe use of protective equipment, and implemented green manure to store carbon. Additionally, hop production has contributed to economic growth by generating income, creating jobs, and promoting gender and generational equality, while also fostering the production of a high-added-value product for the Brazilian agroindustry.

Plain Language Summary

Brazil, one of the world's top beer producers, has started growing hops locally to meet rising demand. This study looked at the social and environmental impacts of

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hop farming on 10 farms in Alagoas, Goiás, and São Paulo using the Ambitec-Agro assessment tool. Results were mostly positive, though some challenges were noted, such as high energy and water use and occasional risks to worker safety. In response, farmers adopted sustainable practices like installing solar panels, using fertigation to save water and inputs, applying green manure, and promoting the use of protective equipment. Hop farming not only supports more sustainable agriculture but also boosts local economies by creating jobs, increasing income, and encouraging gender and generational inclusion. The study highlights the potential of tropical hop production.

1 | INTRODUCTION

1.1 | *Humulus lupulus* L

Humulus lupulus L., commonly known as hop, is a perennial herbaceous vine belonging to the *Cannabaceae* family (Korpelainen & Pietiläinen, 2021), native to temperate climate regions of Europe, Asia, and North America (Bocquet et al., 2018). The female hop cones are predominantly cultivated for the brewing industry, with approximately 97% of global hop production dedicated to this purpose (Almaguer et al., 2014). Beer, a widely consumed beverage worldwide, is valued for its unique sensory characteristics—aromas, flavors, body, and color—achieved through the integration of water, malt, hops, and yeast (González-Salitre et al., 2023). While hops represent a small proportion of the ingredients, they play a pivotal role in defining beer quality and notable health-promoting effects (Rodrigues Arruda et al., 2022; Astray et al., 2020; Karabín et al., 2016), making them indispensable in the brewing process (Gresta et al., 2022).

Hops are highly photoperiod-sensitive and require specific latitudinal conditions for optimal growth, typically between the 45th and 50th parallels. Regions beyond this range may face challenges in cultivation or require artificial lighting to induce flowering (Acosta-Rangel et al., 2024). However, vernalization and dormancy, once thought to be essential for the proliferation of hop flowers, do not affect hops yield or quality (Bauerle, 2019). Successful cultivation also depends on temperatures, annual rainfall, wind conditions, and soil fertility (Paguet et al., 2022). Recently, due to expanding brewing markets, several countries have begun investing in hop cultivation, despite suboptimal conditions (Ruggeri et al., 2024). In Brazil, the world's third-largest beer producer (Barth-Haas Group, 2024), hop cultivation has expanded in the southern and southeastern regions over the past 5 years, supported by farmers' investments, hop associations promotion, and a technical chamber addressing brewing supply chain challenges (Guimarães et al., 2021).

1.2 | *Humulus lupulus* L. cultivation in Brazil

Brazil has 152 registered hop producers (MAPA, 2022) and in 2023 produced an estimated 180 tons in 53 cultivated hectares (International Hop Growers Convention (IHGC), 2023). Of over 15.3 billion liters of beer produced in 2023, 14.7 billion liters relied on imported hops, with only 41.4 million liters using domestically grown hops, while 553.6 million liters combined domestic and imported hops (MAPA, 2024). The Brazilian hop production chain involves multiple sectors, with studies focusing on adapting cultivation to local conditions, including cultivar adaptability, productivity, irrigation, fertilization, lighting, disease control, brewing quality, and economic viability (Jastrombek et al., 2022). To reduce reliance on imported hops, which is crucial for economic sustainability, especially for medium and small brewers, the Brazilian beer industry must address challenges posed by global instability and climate variability (Contin et al., 2023).

Within this context, the objective of this study is to assess the socioenvironmental impacts associated with the domestic cultivation of *H. lupulus* L. in Brazil, applying the Ambitec-Agro tool in 10 reference hop-producing farms in different regions of the country. The research seeks to identify both positive and negative impacts arising from the tropicalization of this crop in Brazil, exploring the potential benefits and challenges of adapting hop cultivation to tropical conditions. The study also focuses on the implications for sustainable development and the consolidation of Brazil's hop production chain.

2 | MATERIALS AND METHODS

2.1 | Selection of farms

Convenience sampling is a form of non-probability sampling that prioritizes the ease of locating or recruiting potential participants. As indicated by the term, participants are selected

primarily for their convenience to the researchers rather than through a structured sampling design (Baker et al., 2013). To identify members of hard-to-reach or hidden populations, non-probability variants of snowball sampling were employed (Goodman, 1961). This approach was particularly relevant, as many hop producers lack websites or social media presence, making it challenging to obtain their contact information. Additionally, the 10 hop producers included in the study were selected based on their significant engagement and interest in voluntarily participating in the research.

Hop producers are distributed across the state of Alagoas in northeast Brazil, which spans an area of 27,830.661 km². The state of Goiás, located in the central-west region, covers an area of 340,242.859 km², while the state of São Paulo, situated in southeast Brazil, has an area of 248,219.485 km² (IBGE, 2023) (Figure 1).

General farms' characteristics, including their location, total area, area dedicated to hop production, activities carried out prior to the implementation of hops (used as a baseline for comparison), and other farm activities are shown in Table 1.

Core Ideas

- Despite agricultural advances, research on the sustainability of tropical hop production remains limited.
- Hop cultivation shows positive socioenvironmental impacts in Brazil.
- Farmers have invested to reduce energy use, improve water and input efficiency, and store carbon.
- Hop production drives economic growth, jobs, gender equality, and high-value products for Brazil's agroindustry.

2.2 | Development

The research was submitted to and approved by the National Research Ethics Commission (77526824.4.0000.5411) due to the involvement of interviews with hop producers for data

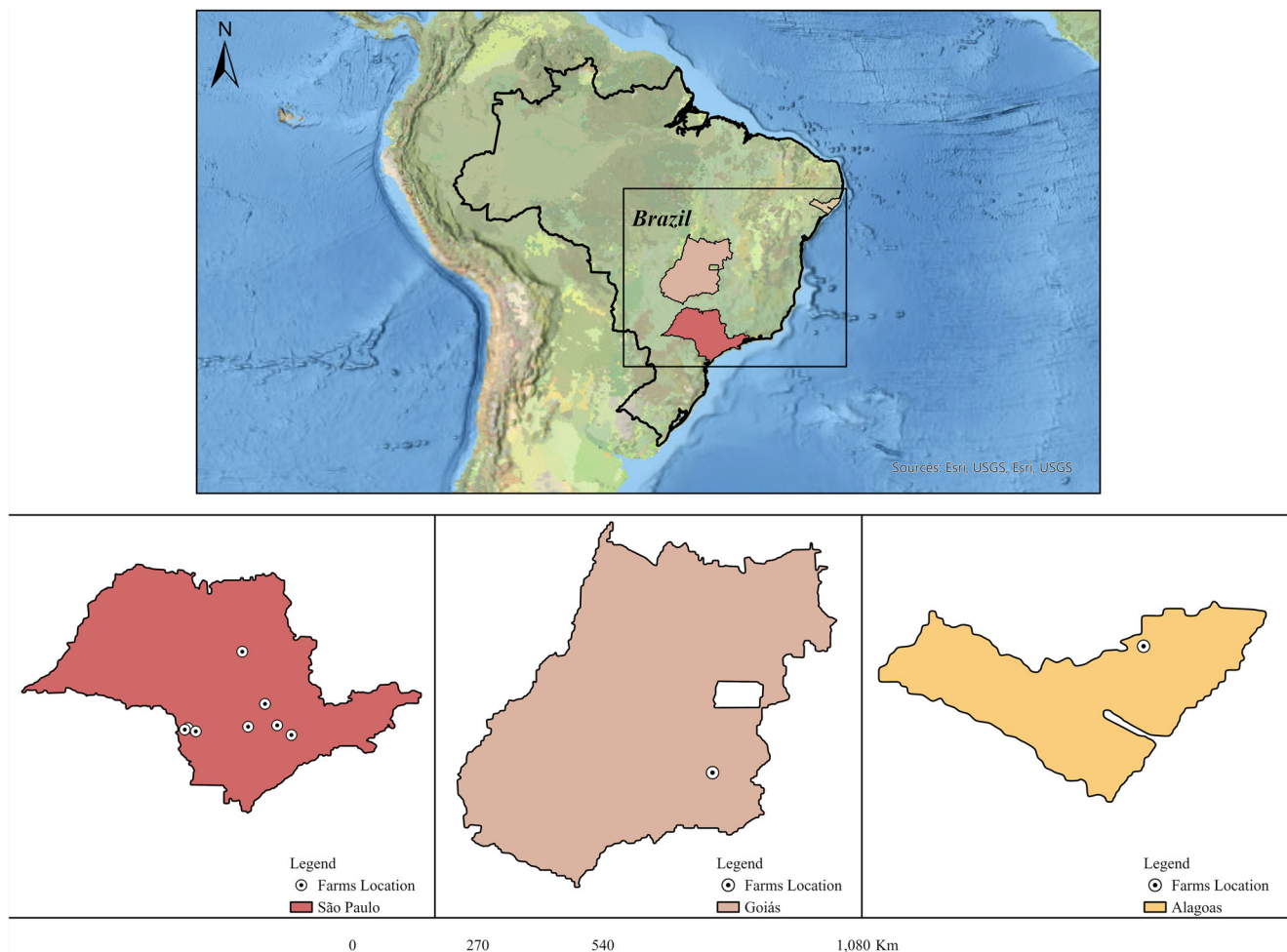


FIGURE 1 Ten reference hop farms included in the study, located in the states of Alagoas, Goiás, and São Paulo, Brazil.

TABLE 1 Farms' characteristics.

Farms	Total area (ha)	Hop area (ha)	Main activity prior to hop cultivation	Other activities
1	271	2	Cereal	Sugar cane, cereals, fruits, cattle, and eucalyptus
2	2.4	1	Grass area	Fruit trees
3	110	0.5	Pasture	Cattle, chicken, sheep, corn, soybean, and coffee
4	150	0.3	Pasture	Sugar cane, corn, and cattle
5	4.8	0.3	Pasture	No other activities
6	70	0.2	Pasture	Black pepper, orange, pasture with eucalyptus
7	9.6	0.2	Pasture	Horse breeding
8	680	3	Pasture	Cattle, corn, and soybean
9	310	1	Soybean	Soybean
10	2.3	0.3	Eucalyptus	Eucalyptus

collection. All participants reviewed and signed the Informed Consent Form, ensuring they were fully informed about the study's procedures and voluntarily agreed to participate.

Data collection was conducted through field interviews or surveys with farmers and managers, focusing on their knowledge of the environmental, social, and economic changes observed as consequences of hop cultivation, production practices, and technologies used in their specific management systems. Interviews were held either in person in the field or remotely via online calls between the hop production manager and the principal investigator, who received training to effectively use the Ambitec-Agro tool, ensuring that all indicators were consistently evaluated across farms.

2.3 | Ambitec-agro

The purpose of the "Environmental Impact Assessment of Technological Innovations in Agriculture" tool (Ambitec-Agro; Rodrigues et al., 2003) is to evaluate the changes in socioenvironmental performance of rural establishments resulting from the adoption of a specific technology, management practice, or production activity. The program is used in ex-post evaluations that consider the impacts effectively observed in the field by objectively checking changes in material quantities, practice allocation times, number and qualification of personnel involved, effectivity of adoption, and conformity with best management practices, among other variables.

The structure of the Ambitec-Agro system considers two main themes: ecological impacts, which relate to natural resources and environmental quality effects resulting from technology or production activity under evaluation, and socioenvironmental impacts, which address the social, cultural, economic, and managerial effects generated. Each main theme encompasses specific aspects, which are further subdivided into a total of 27 criteria (Figure 2). The criteria

are subdivided into 148 indicators, which are based on the theoretical framework outlined by Lewandowski et al. (1999).

The indicators assess the socioenvironmental performance of the adopted technology or productive activity in automated weighting matrices in which change coefficients are assigned based on field evidences and administrative data obtained from farmers' information regarding technology's impact level (Table 2).

Additionally, each matrix features two sets of weighting factors: one reflecting the importance of the indicators, which are standardized in the matrices, and the other corresponding to the geographic scale in which the indicator change coefficient occurred in the studied case. This scale can be classified as occurring at the near, proximate, or surrounding environment (Table 3).

The scale of occurrence can be categorized as follows: Near, when the technology's effects are confined to the crop area or productive field where the affected activity takes place; Proximate, when the technology's effects extend beyond the productive unit but remain within the boundaries of the rural establishment; Surrounding, when the technology impacts an area beyond the farm limits. The scale of occurrence is to capture the magnitude of the observed indicator change coefficient in the specific situation.

Both variables, the effect of the technology innovation (change coefficient), and the scale of occurrence (weighting factor) are gathered through field observations and interviews with the responsible farmer. Indicators were selected for their ability to be quantitatively evaluated in material, area, or proportional units, minimizing biases from the preferences or opinions of the interview subjects. After all change coefficients are sequentially entered into the matrices, the socioenvironmental impact index for each criterion is automatically calculated and presented graphically. Impact indices are computed for the technology under the specific conditions being studied. The impact coefficients for the criteria are calculated using Equation (1):

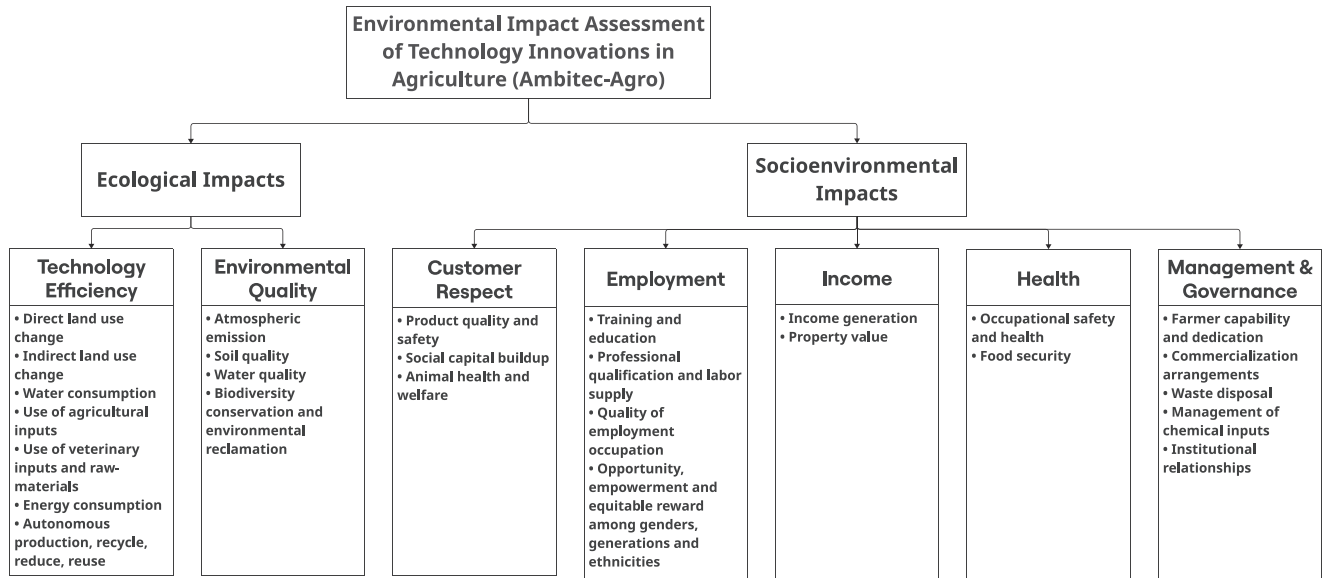


FIGURE 2 Hierarchical structure of impact dimensions, aspects, and criteria considered in the system for “Environmental Impact Assessment of Technological Innovations in Agriculture” (Ambitec-Agro). Two sustainability dimensions (ecological and socioenvironmental impacts) involve their respective seven aspects (technology efficiency, environmental quality, customer respect, employment, income; health, and management and governance), and the 27 subdivided criteria.

TABLE 2 Effects of the technology innovation of Ambitec-Agro.

Effect of the technology innovation	Indicator change coefficient
Significant increase (>25%)	+3
Moderate increase (<25%)	+1
Unchanged (0%)	0
Moderate decrease (<25%)	-1
Significant decrease (>25%)	-3

Note: Adapted from Rodrigues et al. (2003).

TABLE 3 Scale of occurrence of Ambitec-Agro.

Scale of occurrence	Weighting factor
Near	1
Proximate	2
Surrounding	5

Note: Adapted from Rodrigues et al. (2003).

$$EIIc_i = \sum_{j=1}^n C_{ji} S_{ji} I_{ji} \quad (1)$$

where $EIIc_i$ is the environmental impact coefficient of criterion i ; C_{ji} is the change coefficient of indicator j of criterion i ; S_{ji} is the scale of occurrence factor of indicator j of criterion i ; I_{ji} is the importance weighting factor of indicator j of criterion i ; n is the number of indicators of criterion i . The Environmental Impact Index of Technology Innovation, averaging all ecological and socioenvironmental criteria, is then

calculated using Equation (2):

$$EIIIt_i = \sum_{i=1}^n EIIc_i I_i \quad (2)$$

where $EIIIt_i$ is the environmental impact index of technology innovation t ; $EIIc_i$ is the environmental impact coefficient of the criterion i ; I_i is the importance weighting factor of criterion i for the composition of the Environmental Impact Index of Technology t ; n is the number of criteria. The Integrated Impact Index of an agricultural technology is determined by summing the environmental impact coefficient of each criterion, multiplied by its corresponding importance factor. Indices for each aspect are expressed by averaging the impact coefficients of their corresponding criteria (Rodrigues et al., 2003).

Once the indices are obtained, the tool user discusses the results with the farmer or manager and makes the necessary adjustments to ensure the findings' accuracy and relevance. Reports are then prepared, and all farmers receive them to help identify potential environmental improvements that can contribute to sustainable management.

2.4 | Statistical analysis

Statistical metrics are used to analyze the impact of each farm individually, accounting for varying initial conditions as well as differences across reference farms (Rodrigues et al., 2003, 2010). Python was employed to perform the analyses,

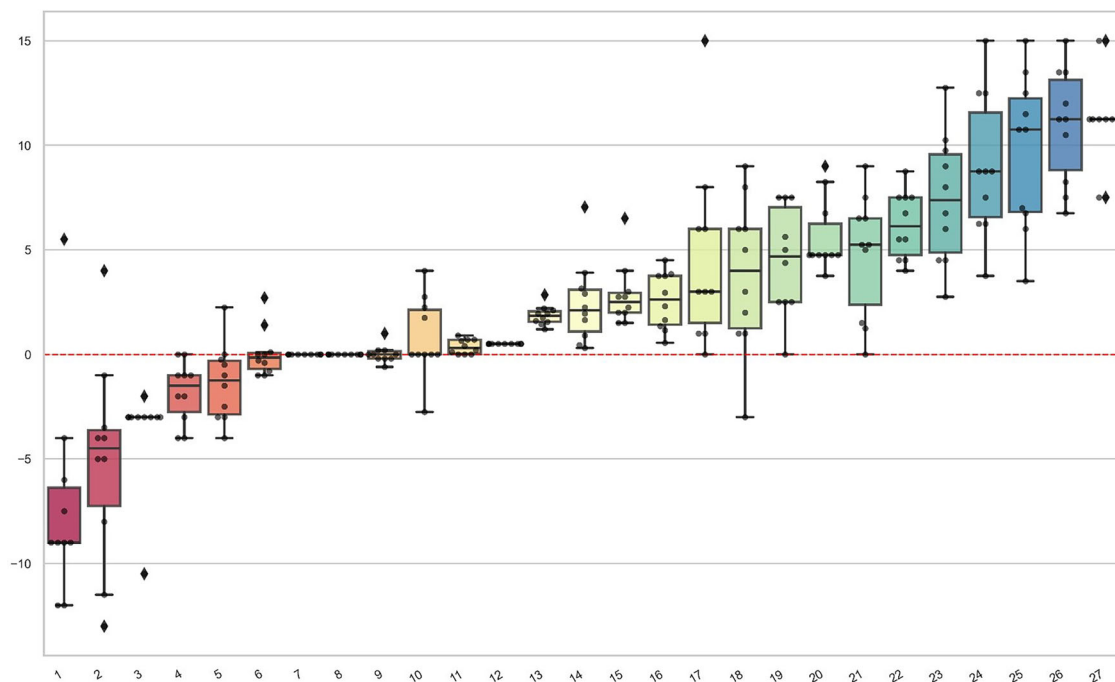


FIGURE 3 Median scores among 10 hop-producing farms, according to impact indices for the 27 environmental performance criteria considered in the Ambitec-Agro system: 1: energy consumption; 2: use of agricultural inputs; 3: use of veterinary inputs and raw materials; 4: water consumption; 5: occupational safety and health; 6: atmospheric emissions; 7: animal health and welfare; 8: food security; 9: water quality; 10: quality of employment/occupation; 11: biodiversity conservation and environmental reclamation; 12: indirect land use change; 13: professional qualification and labor supply; 14: social capital buildup; 15: direct land use change; 16: autonomous production, recycle, reduce, reuse; 17: wastes disposal; 18: income generation; 19: opportunity, empowerment and equitable reward among genders, generations and ethnicities; 20: property value; 21: training and education; 22: product quality and safety; 23: commercialization arrangements; 24: soil quality; 25: management of chemical inputs; 26: farmer capability and dedication; 27: institutional relationships.

with median values by criterion used to address variability among farms. The TensorFlow framework was then applied to visualize the outcomes based on aspects, criteria, and final indices.

3 | RESULTS

Out of the 27 criteria evaluated across the farms, six resulted in negative median values, two showed no change, and 19 criteria were positive (Figure 3). The main effects resulting from hop production across farms, subjected to the specific contexts and transitions relative to previous or concurrent farm productive activities, are described next, following the sequential performance indices shown in Figure 3.

Energy consumption: All farms had increased fossil fuel consumption, except for farm 1, where there was no change since fossil fuels were similarly used in cereal crop production. Hop farms rely on tractors and vehicles for tasks such as harvesting and soil management. Biofuel use remained unchanged in most farms, except farm 2, where biofuel use (ethanol) increased. None of the farms used biomass (e.g., firewood or bagasse). Electricity consumption rose in all

farms due to the high energy demand for light supplementation required in hop production, contributing to a negative environmental impact and higher costs. Some farms installed solar panels to reduce these impacts (criterion 16 in Figure 3), which also helped lower production costs and power farm operations. Farms showed a negative median for energy consumption.

Use of agricultural inputs: Pesticide spraying frequency increased in all farms, except farm 10, which transitioned from eucalyptus forestry to hop cultivation and uses only biological control. Farm 9 showed improvement in pesticide use, reducing reliance compared to its previous soybean cultivation. Most farms saw a negative impact due to increased pesticide diversity (non-alternate active ingredients), but farm 7 maintained careful pesticide management, and farm 9 experienced a positive change. Toxicity levels rose in most farms, except farm 9, which improved from the soybean scenario, and farms 1 and 10, which showed no change relative to their previous practices (cereals and eucalyptus, respectively). Chemical fertilizer use increased in most farms, leading to negative impacts, except for farm 1 (which reduced fertilizer use) and farm 2 (which uses only organic fertilizers). The use of lime and other soil amendments also had a negative

impact in most farms, except farms 1 and 6, where it remained unchanged. Although farms have implemented fertigation to improve water and input efficiency, farms showed a negative median for this criterion.

Use of veterinary inputs and raw materials: Veterinary inputs remained unchanged across all farms, as hop production does not impact veterinary needs. However, all farms showed a negative impact regarding basic raw materials and materials for processing, due to the high demand for inputs such as seedlings, sisal tying ropes, supplemental lighting, wooden supports, and trellises. Additives and supplements had no effect, as none were used in hop processing. Farms exhibited a negative median for this criterion.

Water consumption: The study found that all farms experienced negative impacts on water usage for irrigation due to the high-water demand of hop cultivation. Water use for processing remained unchanged, as hop processing does not require water. Water contamination showed no significant differences across farms, except for farms 5 and 6, which increased pesticide use compared to their prior practices. Farm 6 has higher pesticide usage as it adapts to hop cultivation in the semi-arid Northeast of Brazil. Farm 9 showed a positive outcome, with lower water contamination due to careful pest management and reduced pesticide use. No significant changes in water availability were observed, except for farm 8, which shifted from local reservoirs to a larger one due to hops' high-water demand. Most farms saw no changes in water storage or uptake, except farm 2, which improved with a new irrigation system, while farm 3 experienced negative impacts due to increased water demand and the need for a deeper well. Farms had a negative median impact on water consumption.

Occupational safety and health: The “Workplace Hazards” and “Biological Agents” indicators showed no change in all farms. The “Noise” indicator negatively impacted farms 2, 8, and 9 due to increased tractor use, while farm 3 improved. The exposure to “Vibrations” indicator increased in farm 8 due to tractor use, with no change in the other farms. The “Heat/Cold/Humidity” indicator rose on many farms due to increased field exposure, but farms 1, 2, and 4 saw no change. The “Ergonomic Risks (Falls, Machinery)” indicator increased in most farms due to equipment use, except in farms 2, 4, and 6, with farm 1 improving due to better safety measures. The exposure to “Chemical Agents” indicator increased in farms 3, 5, and 8, while others remained unchanged. Farms showed a negative median impact for this criterion.

Atmospheric emissions: Greenhouse gas emissions varied significantly among the farms. Farms 3, 4, and 7, which were previously pasture areas, showed a positive impact due to reduced tractor use and the implementation of green manure, which improves carbon storage. These farms previously used tractors more frequently for mowing pastures. In contrast, farms 2, 8, 9, and 10 had negative impacts due to increased tractor use for hop cultivation. Farm 2, formerly a grass area,

and farm 8, previously a pasture, required more tractor use for hop production. Farm 9, which was used for soybean cultivation, and farm 10, a former eucalyptus plantation, also had increased tractor use. In the final coefficient balance, farms showed a negative median for this criterion.

Animal health and welfare, and food security: There were no changes observed on any of the farms, as hop production does not directly impact these variables.

Water quality: None of the farms showed organic pollution or visible wastes in water before or after hop cultivation. Turbidity improved on farm 1, which was previously used for cereal cultivation, while no changes were observed in turbidity for other farms. Most farms showed a negative impact for water exposure to pesticides due to sporadic pesticide use, with exceptions for farms 3 and 10, which showed no changes, and farms 1 and 9, where improvements occurred due to previous land uses (cereal and soybean cultivation, respectively). Siltation of water bodies improved on farms 1, 6, and 7, with no changes observed in other farms. Farms showed a median equals zero for this criterion.

Quality of employment/occupation: The “Prevention of Child Labor” indicator showed no changes in any of the farms before or after hop cultivation, all complying with labor regulations. Similarly, the “Workweek up to 44 Hours” indicator did not change in most farms, except farm 9, which showed an improvement after adopting hop cultivation. The “Formal Contract” and “Social Security Registration” indicators improved in farms 7, 8, and 9 due to an increase in the number of workers, while no changes were observed in the other farms, except farm 10, where a decrease was noted due to the owner personally taking over the tasks of land management. Employee benefits indicators, such as “Housing Assistance,” “Food Assistance,” and “Health Care Assistance” improved in farms 1, 8, and 9, while no changes were observed in the other farms, except farm 10, where a reduction was noted due to a decrease in workers. “Transportation Assistance” showed improvements in farms 7 and 9, with no changes in the other farms. Farms showed median equals to zero for this criterion.

Biodiversity conservation and environmental reclamation: Improvements in the “Native Vegetation” indicator were observed in farms 1, 2, 4, 6, and 7 due to native tree planting following the introduction of hop cultivation. The unique nature of hop production in Brazil attracts visitors, motivating producers to enhance their farm landscapes. On farm 6, the Rural Environmental Registry was regularized, requiring native tree planting for compliance, while farm 7 increased tree planting as wind barriers. Other farms showed no changes. The presence of wild fauna, such as birds and bees, increased on farms 2, 6, and 9, likely drawn by the scent of hops and associated cover crops. The “Degraded Soils” indicator improved in farms 2, 7, 9, and 10 due to hop cultivation, with notable improvements in farms 9 and 10, previously used for soybean and eucalyptus. No changes were observed

in the “Traditional Landraces/Breeds,” “Permanent Preservation Areas,” or “Legal Preserves/Set Aside Areas” indicators. Farms showed positive median for this criterion.

Indirect land use change: Competition with food production activities had positive results for all farms. Although hop is not a food product in the traditional sense, it plays a crucial role in agroindustry, particularly in beer production. As an emerging crop, domestic hop production helps reduce reliance on imports and supports the growing agroindustry. None of the farms caused displacement of non-agricultural areas or conflict over land ownership or use by local communities. Farms showed a positive median for this criterion.

Professional qualification and labor supply: The “Untrained manual work,” “Trained/specialized,” and “Specialized technical/engineering” indicators improved in all farms due to the increased demand for labor in hop production. The “Technician (Professional Qualification)” indicator also improved in most farms, except farm 9, which did not employ technicians. The “Temporary (Labor supply and hiring conditions)” indicator improved in all farms except farm 6, where the farmer relies on workers from other crops. Improvements in the “Permanent (Labor supply and hiring conditions)” work indicator were observed in most farms, except farms 4 and 10, where the farmers are the only permanent workers. The “partner worker/sharecropper” indicator showed no changes in any of the farms. Farms 2, 3, and 7 saw an increase in the “Family worker” indicator due to family members participating in hop-related activities, while the other farms showed no changes. Farms showed a positive median for this criterion.

Social capital buildup: “Cultural integration with employees and their families” improved in farms 2, 7, and 9 through hop harvest parties and celebrations, with other farms planning similar activities. “Commitment to social movements” increased in farms 8 and 9, where farmers became involved in labor unions and cooperatives, while other farms showed no change. The “Preservation of historical/artistic/cultural heritage” indicator improved in farms 2, 8, and 9, where hop registration of brands and trademarks highlighted Brazilian origins and biomes, while other farms saw no changes. “Responsiveness to community demands” improved in farms 1, 5, 7, 8, 9, and 10, which hired more local workers, while other farms maintained the same workforces. “Community outreach and environmental education” improved in farms 1, 2, 3, 4, 8, and 9 through school visits, with other farms showing no recent changes. “Technology and knowledge transfer programs” improved in all farms through courses and training for employees and the community. Farms showed a positive median for this criterion.

Direct land use change: The yield per unit area (land-saving effect) showed a positive impact across all farms, mainly due to higher yields and crop value per hectare. Fire prevention improved through daily monitoring of hop fields, although

this was already well established in farms 3 and 6. Carbon storage increased in most farms, thanks to the use of green manure and tree planting, but farm 5 did not adopt these practices and saw no increase. Hop cultivation, whether as an additional or sole crop, contributed to product diversification. Farms showed a positive median for this criterion.

Autonomous production, recycle, reduce, reuse: Half of the farms (1, 2, 3, 5, and 8) improved their energy practices by investing in solar panels to meet the high electricity demand for light supplementation in hop production, which requires up to 16 h of light per day. This led to energy savings through thermal utilization. All farms used organic fertilizers, and most incorporated green manure, although farms 2 and 5 had not yet adopted this practice, though they planned to in the future. Biological control was implemented on all farms except farms 2 and 5, with plans for future adoption. Farms showed a positive median for this criterion.

Wastes disposal: The implementation of hop crops led to improvements in “Selective collection (domestic waste)” indicator in farms 3, 9, and 10. “Composting, recycling, and reuse (domestic waste)” also improved in farms 2, 3, and 9 following the introduction of hops. Similarly, “Sanitary disposal (domestic waste)” saw advancements in farms 2, 3, and 10. For the remaining farms, these indicators remained unchanged. Regarding “Reuse/recycle (production wastes),” there was significant progress in many farms, where hop residues are repurposed in various ways, except in farms 1, 7, and 8, which showed no change. Improvements in “Adequate disposal/Final treatment (production wastes)” were observed in several farms, except farms 1, 2, 4, and 5. Farms showed a positive median for this criterion.

Income generation: The “Security (income obtaining warranty)” indicator varied among farms. Farms 1, 5, and 10 saw improvements due to their previous land uses—cereal crops, pasture, and eucalyptus—which had income limitations. Cereal crops provided annual income, while hop cultivation offers biannual income. Farm 5’s pasture generated lower income, and eucalyptus in farm 10 provided slower earnings, whereas hop production ensured more consistent profits. In contrast, farms 3, 4, 7, and 8, previously pasture areas, saw declines in this indicator. Hop cultivation’s income potential is still uncertain, with some farms supplementing income from other crops due to high initial investment. Farm 9 also experienced a decline compared to the stable income from soybean cultivation. The “Stability (reducing seasonality)” indicator followed a similar trend, with farm 8 unchanged. Hop production in farm 8 ensures year-round income, comparable to livestock cycles. Farms 2 and 6 saw no change, as farm 2 did not previously engage in crop production, and farm 6’s hop income was similar to pasture income. The “Distribution (salaries and benefits paid)” indicator improved across all farms due to labor opportunities from hop cultivation. The “Diversity of income sources”

indicator also increased in most farms, as hop production became an additional or primary crop, except for farm 2, where income remained uncertain due to an incomplete first harvest. The total earnings indicator showed significant variability. Farms 1, 2, 5, and 6 reported no change, while farms 4 and 7 saw decreases. Conversely, farms 3, 8, 9, and 10 showed improvements. This variability is linked to the high initial investment and the current period of crop adaptation, though significant income growth is expected due to hops' high added market value. Overall, farms showed a positive median for this criterion.

Opportunity, empowerment, and equitable reward among genders, generations, and ethnicities: The indicators for "Involvement opportunities and enhancement of women's participation" and "Equitable reward for the productive activities of women" improved in most farms due to increased hiring and involvement of women in hop production. However, farm 10 showed no change, as the owner is the sole worker with occasional help from temporary male workers. The "Emancipation and recognition of women's choices" indicator improved in farms 1, 2, and 7, where women assumed leadership or management roles in hop production. The "Involvement opportunities and enhancement of the participation of the young and elderly" and "Equitable reward for the productive activities of the young and elderly" indicators improved in most farms, except farms 2, 7, and 10, which did not employ young or elderly workers. Only farm 1 showed improvement in the "emancipation and recognition of choices of the young and elderly," as these workers held leadership positions and had decision-making authority in hop activities. The "Equality of opportunity for ethnic groups" and "Mutual respect and cultural appreciation" indicators showed no changes across any farms. Farms showed a positive median for this criterion.

Property value: All farms presented a significant increase in the "Facilities improvement investments" indicator due to investments in hop field infrastructure, post-harvest facilities, electricity connections, and solar panels. These improvements enhanced the overall farm value. The "Conservation of natural resources" indicator remained unchanged across all farms. The "Prices of produce, goods, and services" indicator rose for farms that had completed harvests, reflecting the high-value nature of hops. The "Compliance with legislation" indicator improved in farm 9 due to better hiring practices related to hop production, while the other farms saw no changes. The "Infrastructure, public services, tax policy, etc." indicator improved in farms 9 and 10 but remained unchanged for the others. Farms showed a positive median for this criterion.

Training and education: The "Short-term local training" indicator showed improvements in all farms except farms 4 and 10, as these farms are still in the early stages of hop cultivation and have minimal staff. Farms 1, 3, 7, 8, and 9 saw improvements in the "Specialization" indica-

tor due to specific training for workers involved in hop production. The "Technical (Level of training)" indicator improved in farms 1, 2, 6, 8, 9, and 10, where workers received technical-level training for hop management. However, no changes were observed in the "Regular education," "Basic (Level of training)," and "Higher (Level of training)" indicators. Farms showed a positive median for this criterion.

Product quality and safety: "Chemical contaminant reduction" improved in farms 1 and 9, as hop management practices were less input-intensive compared to previous crops (cereals and soybean). No changes were observed in the other farms. "Biological contaminants" remained absent in all farms, and no changes were noted in this indicator. The "Post-harvest procedures" indicator reached its maximum level on farms 1, 3, 5, 8, and 9, as they process hops through all production stages (crop to packaged pellets). Farms 2, 4, and 6 showed improvements but only process a few stages, such as drying, sending hops to other producers for the remaining stages (pelletization and vacuum and packing). Farms 7 and 10 did not show changes, as they process hops in other farms. The "Availability of input suppliers" and "Reliability of input suppliers" indicators improved in all farms, except farm 9, where these were already well established due to its previous soybean cultivation. Farms showed a positive median for this criterion.

Commercialization arrangements: Improvements in "Direct/anticipated/cooperated sales" were seen in most farms, except farms 4, 6, and 7, which did not previously engage in these sales and still lack such activities. Farm 9 experienced a decline in this indicator due to existing anticipated sales arrangements previously tied to soybean production. The "local processing" indicator improved across many farms, driven by on-site hops processing, with at least initial stages like drying being performed in most farms. However, farms 7 and 10 remain reliant on external producers for complete hops processing. All farms, except farm 7, showed improvements in "Local storage," with the latter continuing to use existing facilities. "Transportation Means" improved in farm 5, which acquired a new vehicle for hop transport, while others maintained their existing vehicles. The "Advertising and trademark" indicator increased across all farms, with the development of hop-specific brands, labels, websites, and social media efforts. "Linkage to other products, services, and activities" improved in several farms, reflecting the integration of hop production with other on-farm activities, except for farms 1, 4, 5, and 8. "Cooperation with other local farmers" increased in most cases, except for farms 6, 7, and 10. Farms showed a positive median for this criterion.

Soil quality: The study found that farms 4, 5, 6, and 10 showed no changes in erosion levels, as their soils were not eroded before hop cultivation. However, the other farms

experienced improvements in erosion control after introducing hops. All farms saw reductions in organic matter loss and nutrient leaching due to the deep roots of hop plants, which enhance soil nutrient retention compared to previous land uses, whether pasture or other crops. Soil compaction improved in most farms, except for farms 2 and 8, where no changes were observed because the soil was not compacted initially. Farms showed a positive median for this criterion.

Management of chemical inputs: All farms reported improvements in the use of individual protection gear and record keeping of treatments. Safe storage of chemical inputs increased in most farms, with the exception of farms 6 and 7. Similarly, calibration and checking of spraying equipment improved across many farms, although farms 1, 6, and 7 showed no changes in this indicator. The appropriate destination of empty containers saw advancements in farms 2, 3, 4, and 10, while no changes were noted in the other farms. Farms showed a positive median for this criterion.

Farmer capability and dedication: The “Training directed to the activity” indicator improved in all farms due to increased training for farm managers in hop cultivation, including specialized courses. The “formal planning model” improved with better planning, including the use of spreadsheets tailored to hop production. The “Certification system/labeling” indicator showed progress as hop brands developed, with analytical monitoring of essential oil quality for certification. All farms improved in these three indicators. The “Dedicated working time” indicator improved in all farms except farms 1 and 6, where others manage hop cultivation. “Family engagement” increased in most farms, except farms 1 and 4, which saw no change. The “Use of accounting system” improved in most farms due to the need for precise financial management, although farms 2, 4, 6, and 7 did not adopt such systems. Farms showed a positive median for this criterion.

Institutional relationships: All farms reported improvements in “Access to Formal Technical Assistance,” driven by the challenges associated with cultivating hops. Similarly, all farms showed increases in “nominal technological affiliation,” reflecting the unique and high-value nature of hop cultivation in Brazil. Most farms also experienced growth in “rural association engagement/cooperative,” supported by increased farmer participation, with the exception of farms 2 and 7. Improvements in “Legal Consultancy/Conformity Assessment” were observed in farms 9 and 10, while no changes were noted in the other farms. Farms showed a positive median for this criterion.

The impact scores per farm’s aspects indicate that “Environmental Quality,” “Customer Respect,” “Employment,” “Income,” and “Management and Governance” showed positive outcomes across farms. “Technology Efficiency” and “Health” aspects presented the lowest scores (Figure 4).

The Environmental Impact theme index is based on the “Technology Efficiency” and “Environmental Quality”

aspects. Farm 7 showed the highest score, mainly due to its excellent “soil quality,” which improved through management practices enabled by hop plants deep root systems, such as fertigation and green manuring, reducing erosion, organic matter loss, nutrient depletion, and soil compaction. These practices enhanced soil water and nutrient retention. Farm 5 scored the lowest due to increased pesticide use, including more frequent applications of higher toxicity active ingredients, along with increased use of soil conditioners and chemical fertilizers. Both farms were previously pastures. Other farms showed balanced scores with low variability, though farms 6 and 8 had negative scores due to specific issues. Farm 6’s high pesticide and chemical fertilizer use led to a negative score in “use of agricultural inputs,” while farm 8’s significant energy consumption increase was linked to the higher electricity demands for hop cultivation compared to pasture.

The Economic Impact Index, represented by the aspects “Employment” and “Income,” showed varying results across farms. Farm 9 had the highest score, mainly due to significant improvements in the “training and education” criterion, driven by local short-term training programs, informal sessions, and specialization training for hop cultivation professionals—training not required with previous soybean cultivation. Farm 4 showed the lowest score due to limited income from hop production on its small 0.3-ha area, with the farmer managing production independently and relying on temporary, untrained workers for manual tasks during harvest.

Despite farm 4’s low performance, all farms showed positive economic impacts. This was largely due to the increasing need for specialized training in hop cultivation, leading to improved labor conditions, better compliance with labor regulations, and more employee benefits. The two harvests per year provided income stability and reduced seasonality, while income diversification grew as many farms continued to cultivate other crops alongside hops. Investments in infrastructure like irrigation systems and specialized facilities raised property values, and the development of hop brands added value to both the products and the Brazilian agroindustry.

The Social Impact Index, represented by the aspects “Customer respect,” “Health,” and “Management and Governance,” showed the most balanced performances across farms, achieving the highest average values. This positive outcome is linked to the social benefits of hop production, especially the improved skills and dedication of farmers in hop cultivation compared to their previous crops. The uniqueness of hop production in Brazil has also strengthened institutional relationships, enhancing these social benefits. Additionally, better management of chemical inputs contributed to the index, reflecting farmers’ careful handling of workers’ occupational exposures, personal safety equipment, and handling of inputs, along with thorough record-keeping of treatments. Emphasis on product quality and safety has been supported by reliable input suppliers.

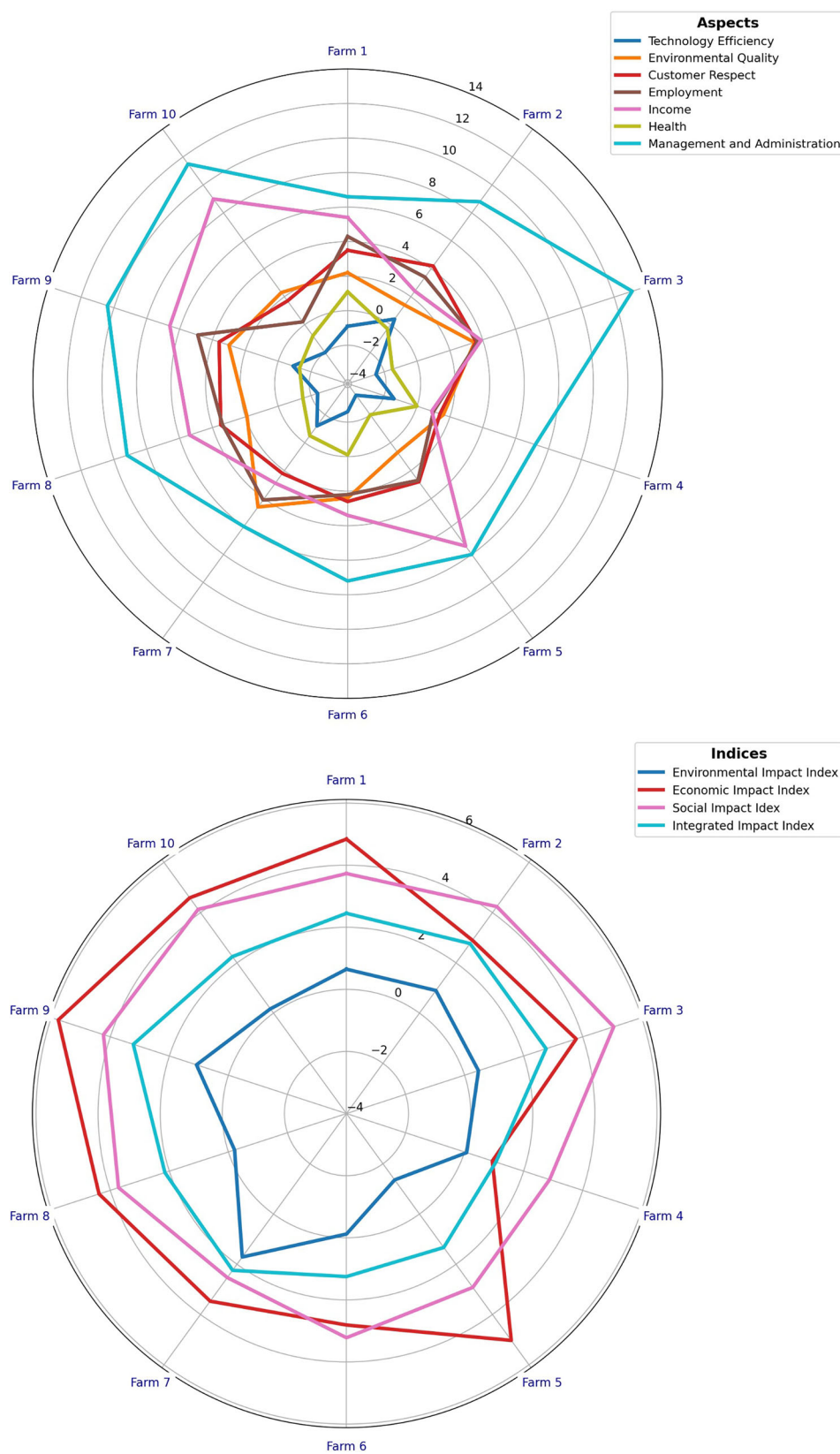


FIGURE 4 Top graph: Aspect scores for all reference farms. Lower graph: Environmental, Economic, Social, and Integrated Impact Indices for all reference farms.

The Integrated Index, comprising the Environmental, Economic, and Social Indices, shows positive values for all farms. This indicates that, when comparing the previous scenarios for each evaluated farm relative to hop cultivation, all farms experienced positive socioenvironmental impacts.

4 | DISCUSSION

The uniformity observed in the Integrated Index across the 10 farms is likely due to a combination of factors, such as shared characteristics in the producers' strategies or standardized management practices typical of hop cultivation, which tend to produce similar profiles among farms. The results also show positive outcomes across most criteria, with occasional negative results in certain areas. Energy consumption, for instance, is impacted by the insufficient day length in subtropical and tropical climates, a key limitation for hops production (Gallardo et al., 2025). To address this limitation, farmers supplement light for over 15 h (Jastrombek et al., 2022), mostly using LED lighting with solar panels powering it, which also benefits other crops or the farm as a whole. The use of agricultural inputs and water consumption showed negative median indices due to the high demand for both.

Hops typically require significant irrigation in most commercial fields to optimize yield and quality, although water needs vary depending on local climate conditions (Turner et al., 2011). However, farms using fertigation systems save water while applying nutrients efficiently (MAPA, 2022). The increased use of pesticides is also noticed in this aspect. However, several farms have begun adopting alternative practices, such as biological control for pests and disease management.

The demand for raw materials, such as seedlings, sisal, lighting, supports, and trellises, results in high input costs, which negatively impact the supply chain. Occupational safety is a concern due to workers' exposure in the fields, though farmers encourage and enforce the use of protective equipment. High atmospheric emissions occur due to frequent tractor use for hop management, but farmers have implemented green manure to store carbon. Additionally, hop rhizomes, which can live up to 14 years (Gutiérrez et al., 2024), further contribute to carbon storage.

Regarding the positive findings, the study revealed favorable median indices in the three dimensions of sustainability. The social and economic dimensions are closely interconnected largely due to increased involvement of hop farmers in associations and cooperatives, as well as their commitment to improving their skills and knowledge compared to previous crops. This shift reflects their focus on enhancing expertise and optimizing hop cultivation to produce high-value products for the Brazilian agroindustry, ultimately boosting profitability. Farms show improvements in commercialization arrangements, property value, wastes disposal,

and labor-related criteria, reflecting the implementation of infrastructure, equipment, and trained personnel to support all stages of hop processing.

Moreover, hop production has driven economic growth by generating income, creating jobs, promoting gender and generational equality, and contributing to the production of a high-value product for the Brazilian agroindustry. Since natural hops are less commonly used in commercial brewing, and the process of producing hop pellets involves drying, grinding, and extrusion (Duarte et al., 2024), these techniques increase the involvement and value of hop farmers' properties. On-farm innovation also helps hop farmers increase profits, adapt to environmental changes, and improve sustainability. This is important for policymakers and research groups focused on rural development. Initiatives that fund farmer-led innovation and promote reinvestment can lead to better long-term environmental outcomes while supporting short-term rural livelihoods (Comi, 2020).

Our findings also demonstrate advances in environmental aspects, due to improvements in soil quality, biodiversity conservation, and environmental reclamation, as well as both direct and indirect land use changes following hop production. This is attributed to hop producers adopting more organic practices, such as biological control, cover crops, and organic fertilizers. Developing reliable methods for controlling pests, diseases, and weeds will be essential for the success of organic hop growers. These strategies may need to be tailored to local environmental conditions and cultural practices.

The use of cover crops will be crucial in supporting beneficial insects, enhancing soil quality, and increasing nutrient availability (Turner et al., 2011). *Humulus lupulus* L. offers potential for developing innovative socioecological models that integrate traditional knowledge, cultural practices, agricultural techniques, and sustainable management approaches. These efforts aim to address challenges in the agri-food system, promoting circular economy principles (Viriato et al., 2024) and diversification in production systems (Alfaro-Saiz et al., 2024).

Several recent studies have utilized the Ambitec-Agro tool to assess the impact of agricultural innovations in Brazil, for example, to assess the impacts of biogas production implemented by family farmers in a cooperative agroenergy condominium (Porto et al., 2021); to evaluate the transition of conventional dairy farming to organic systems in family-based agriculture (de Oliveira et al., 2022); to understand the transition toward sustainability through the perception about the value created and appropriated by integrated poultry farmers (Demattê Filho et al., 2023); to explore how bioeconomy principles are integrated into farms and to assess the socioenvironmental benefits (Cidón et al., 2024); to evaluate the impacts of the adoption of a variety of arracacha on agricultural sustainability and productivity (Navarro-Niño et al., 2024).

The Ambitec-Agro tool was also used to evaluate the potential of Crop-Livestock Integration (Galharte & Crestana, 2010) and Crop-Livestock-Forestry Integration in Brazil (Rodrigues et al., 2017) and in Colombia (Vásquez-Urriago et al., 2024), which revealed positive and satisfactory socioenvironmental gains. Additionally, the tool was also applied to introduce a module of impact indicators for Information and Communication Technologies (Ambitec-TICs) and evaluate its application across several technology adoption cases in agricultural projects (Pinto et al., 2021). These works are examples of different uses of Ambitec-Agro tool in the agricultural field, although it has not yet been applied to hops.

The current findings on hop cultivation offer farmers valuable insights into both the positive and negative impacts of their practices, identifying areas for improvement to achieve more sustainable outcomes. This approach can promote the adoption of environmentally and socially sustainable hop cultivation methods, boosting production in Brazil and positioning the country to meet domestic demand and eventually expand into international markets. Future studies could address several challenges to more comprehensively evaluate the socioenvironmental impacts of hop production in Brazil, such as expanding the number of farms included in the analysis. While this study focused on 10 farms, representing about 6.5% of all producers, increasing the sample size would improve the robustness and generalizability of the findings. Additionally, exploring other tools to empirically assess the environmental impact of hop production, such as collecting precise data on water and soil quality, would provide a more detailed understanding of its effects.

5 | CONCLUSION

Socioenvironmental impact indices were attained from 10 hop farms in Brazil using the Ambitec-Agro tool, revealing positive outcomes across social, economic, and environmental dimensions compared to previous land uses such as pasture or other crops. Economic gains ranked highest, followed by social and environmental improvements. These results suggest that the tropicalization of hops in Brazil is fostering sustainability across all three pillars.

Moreover, the socioenvironmental data obtained from hop production allows for identifying opportunities to minimize input usage, lower production costs, reduce environmental impacts, ensure the social well-being of workers, and contribute to local sustainability. Additionally, more sustainable hop cultivation alternatives can be adopted, boosting production in Brazil and positioning the country to meet national and potentially international market demands. Evaluating Brazilian hop production with the Ambitec-Agro tool offers a promising, low-cost, and practical platform that covers a wide range of agricultural technologies.

AUTHOR CONTRIBUTIONS

Viviany Viriato: Conceptualization; investigation; methodology; project administration; writing—original draft. **Geraldo Stachetti Rodrigues:** Supervision; validation; visualization; writing—review and editing. **Marcio Renato Nunes:** Supervision; validation; visualization. **Abebe Belay Adege:** Data curation; formal analysis. **Filipe Pereira Giardini Bonfim:** Supervision; validation; visualization; writing—review and editing.

ACKNOWLEDGMENTS

We would like to thank all the participants who were interviewed for their valuable contributions. We also extend our gratitude to São Paulo State University, University of Florida, and Embrapa Meio Ambiente for the opportunity to utilize their resources and collaborate as partners. Special appreciation goes to Molges Kidane Biru for his assistance in creating the map.

The article was funded by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil (Grant Number: 2023/12485-0). The Article Processing Charge for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil (ROR identifier: 00x0ma614).

[Correction added on 27 October 2025, after first online publication: FAPESP and CAPES funding has been added.]

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

The project was approved by the National Research Ethics Commission (77526824.4.0000.5411).

ORCID

Viviany Viriato  <https://orcid.org/0000-0002-3398-9797>

Geraldo Stachetti Rodrigues  <https://orcid.org/0000-0002-5604-3531>

Marcio Renato Nunes  <https://orcid.org/0000-0002-3674-279X>

Abebe Belay Adege  <https://orcid.org/0000-0002-7649-9739>

Filipe Pereira Giardini Bonfim  <https://orcid.org/0000-0003-4808-9836>

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How to cite this article: Viriato, V., Rodrigues, G. S., Nunes, M. R., Adege, A. B., & Bonfim, F. P. G. (2025). On-farm observations of socioenvironmental impacts of *Humulus lupulus* L. cultivation in Brazil. *Agronomy Journal*, 117, e70175. <https://doi.org/10.1002/agj2.70175>