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## Abstract

French organic vegetable farms are diverse, ranging from complex biodiversity-based systems, with many vegetables, to simple input-based systems with few vegetables, suggesting potentially different impacts on the environment. We used life cycle assessment (LCA) to assess the impact of three contrasted farms: MF, a microfarm with a high crop diversity and a low input level, SP, a medium sized farm specialised in sheltered production with a low crop diversity and a high input level, and OP, a large farm specialised in outdoor production with intermediate input level and crop diversity. To cope with the complexity of organic vegetable farms, we opted for a system LCA, based on farm inputs and output for a one-year period. Using mass-, and area-based functional units, we analysed the impacts on climate change, land competition, biodiversity, and the use of plastic.

Per ha, differences between the systems were large for climate change. SP had the highest impacts, whereas OP had the lowest impacts. Expressed per kg, differences between the systems for climate change were much smaller, even ranking differently. OP used much less plastic but performed worse on biodiversity and land competition. Despite its higher yield, SP did not perform better than other farms on impacts per kg for climate change, and plastic use. The impact on on-farm biodiversity, showed contrasting results compared to the other impacts. It highlighted the importance of semi-natural habitats. The quantification of plastic use echoed growing concerns on (micro-)plastic pollution in agricultural soils and landscapes.

Keywords: life cycle assessment, agroecology, horticulture, organic farming, biodiversity

## 1. Introduction

French organic vegetable farms are diverse, ranging from complex biodiversity-based systems, to simple input-based systems (Pépin et al., 2021). In this conceptual dichotomy, the first pole can be considered as “agroecological organic farming” and is characterized by low input and biodiversity-based practices, combining a large range of crops, intercrops and non-crop biodiversity to help maintaining the farming system’s health and resistance to disturbance, in a systemic approach (Morel and Leger, 2016). On the other hand, the second pole can be considered as “conventionalised organic farming” and is characterized by growing few vegetables with input-based practices in a crop approach. Beyond the binary “agroecological or not” distinction, a gradient of farms exists between these two poles, with different levels of agroecology. The heterogeneity of input use and farming practices may lead to different environmental impacts of farms, but these have not been quantified yet. The objective of this paper is to assess the environmental performances of organic vegetable farms that are contrasted by their agroecological functioning.

In this study, we assessed the environmental performances, using life cycle assessment (LCA) methodology, on three French organic vegetable farms, assessing impacts on climate change, land occupation, biodiversity decline, and the use of plastic.

# 2. Materials and methods

## 2.1. Life cycle assessment

Life cycle assessment (LCA) is a multi-criteria assessment method that quantifies a range of potential environmental and health impacts and resource depletion issues that are associated with goods or services.

The impact categories considered were:

- Climate change (CC) for time horizon 100 years, which corresponds to the greenhouse gas emissions, expressed in kg $CO_2$ eq. It was calculated using ReCiPe 2016 (Huijbregts et al., 2016).
- Land competition (LC) which is the land occupied by the system, expressed in $m^2a$. The method used was CML-IA non-baseline (Guinée et al., 2002).
- On-farm biodiversity (BD), which was assessed using SALCA-BD (Jeanneret et al., 2014) adapted to vegetable production. This method assesses the potential impacts on terrestrial biodiversity of eleven indicator species groups of land-use types (including semi-natural habitats) and management practices. Field level impact scores were aggregated at the farm level.

The use of plastic was also assessed, although it is not an LCA indicator. It was calculated by summing plastic material weights used yearly on the farm. The weights of materials that lasted several years was divided by their lifespan resulting in an average annual value. Plastic materials included tunnel cover and plastic components, (fert)irrigation pipes and drips, mulching sheets, fleeces for pest protection, pots and trays for purchased and farm-made seedlings, plant support clips and strings.

We analysed the farms as a whole in a farming system LCA: we considered the total annual production of vegetables and the total inputs without specifying which input was used for which crop.

We expressed impacts by two functional units (FU), except for BD which is expressed by a unitless single score for the whole farm:

- per hectare of farmland occupied during a year; the farmland included cultivated land and on-farm semi-natural habitats (e.g. hedges, meadow, ruderal area, space between the tunnels) as they may provide regulation services. We did not include off-farm land associated with production of inputs.
- per kg of vegetables produced over a year.

We assessed the impacts from cradle to farm gate. The foreground system included: field preparation, fertilisation, sowing and planting, weeding, pest and disease control, irrigation, harvesting and on-farm storage. The background system included the production of fertilisers, main material and energy used for production and on-farm storage. The construction phase of the tunnels was considered, but not the production phase of tractors and pumps. The processes beyond the farm gate such as transportation, packaging, retail, use, and end of life were not included.

## 2.2. Description of the farms

We chose three farms who took part in the survey by Pépin et al. (2021) that characterizes the diversity of French organic vegetable farms. These farms however are specific cases with individual characteristics and should not be considered as fully representative. The farms are 1) MF: a microfarm with a high crop diversity and a low input level, 2) SP: a medium sized farm specialised in sheltered production with a low crop diversity and a high input level, and 3) OP: a large farm specialised in outdoor production with intermediate input level and crop diversity (**Table *1***).

**Table 1. Characteristics of three French organic vegetable farms**

| **Characteristic** | **Farm type** | | |
|---|---|---|---|
| | Microfarm (MF) | Sheltered production (SP) | Outdoor production (OP) |
| Outdoor vegetable area | 0.16 ha | 0 ha | 17.5 ha |
| Sheltered vegetable area | 0.12 ha | 2.0 ha | 0 ha |
| Number of vegetables | 35 | 6 | 20 |
| Yield | 35 t/ha/yr | 67 t/ha/yr | 9 t/ha/yr |
| Agroecology | Agroecology ++<br>Inputs - | Agroecology -<br>Inputs ++ | Agroecology +<br>Inputs + |

MF was a recent microfarm in the Brittany region producing 35 different types of vegetables in a 1200 $m^2$ tunnel and a 1600 $m^2$ outdoor field. The farmer was inspired by a French farming trend called "market gardening on living soil" (maraîchage sur sol vivant) that aims to protect and feed the soil - and its living organisms such as earthworms, bacteria and mycelia – by combining no tillage and permanent cover of organic mulch and plants. Fertilisation consisted of compost of green waste, manure and manure pellets to bring long-term fertility and avoid short-term nitrate deficiency due to microbial activity. Reusable fleece was used to avoid insect problems and copper sulphate was used against blight on tomatoes (the only crop receiving treatment). The selling outlets were vegetable boxes, a local market, shops and restaurants in the nearby village.

SP produced mainly tomato and cucumber in summer and salad in winter, in 33 tunnels for a total cultivated area of 19840 $m^2$, located in the Provence-Alpes-Côte-d'Azur region. One or two one-month sorghum cover crops were grown annually in ca. 25% of the tunnels to bring fresh biomass to the soil. Fertilisation consisted of industrial manure pellets and beet vinasse before each crop. Single use plastic mulch was used against weeds. Purchased insects were released in the tunnels to control pests (macrolophus, chrysopa) and for pollination (bumblebees). The farmer sold the vegetables to wholesalers in France and Germany under the biodynamic label.

OP produced vegetables on 24 ha of open-field, in Brittany, following a four-year rotation: potato / rye followed by turnip / cabbages (cauliflower, green cabbage, savoy cabbage, Brussel sprouts, kale) / various vegetables (carrots, onions, squash, etc.). Fertilisation consisted of cow and poultry manure three years out of four. Weeding was mechanical, and thermal (gas) in carrot crops. Reusable fleece was used to avoid insect problems on some vegetables but overall pest and disease control was very limited. The farmer sold the vegetables locally to organic stores and wholesalers, and at local markets.

# 3. Results and discussion

## 3.1. Climate change

The environmental impact on CC of the three farms differed according to the functional unit. Per ha of land occupied, OP had the lowest impact for CC (1.3 t $CO_2$ eq./ha, **Fig. *1***), due to its low input use. SP had the highest impact (13.3 t $CO_2$ eq./ha). This system produced two to three crops per year, leading to a higher input use. MF had an intermediate value (7.5 t $CO_2$ eq./ha). Part of this farm had one crop per year (outdoor) and the other part had two crops per year (tunnel). The climate change impact of SP was 10.6 times higher than that of OP.

Per kg of vegetable, CC impact of MF and SP was similar (215 and 198 g $CO_2$ eq./kg, respectively), while impact of MF was 1.6 times higher than that of OP (134 g $CO_2$ eq./kg). This difference was much smaller than for impacts per ha because OP yielded less than MF. The higher productivity of SP allowed it to have similar or slightly lower climate change impact per kg than MF despite a higher input use per ha. However, compared to OP, the higher productivity per ha of does not fully compensate its higher impact.

The components of the system contributed differently according to the farms. For MF, diesel was the main contributor (49%) to climate change, mainly pumps for irrigation, before the tunnel (27%). The impact of tunnels was mainly due to the galvanized steel structure, considered to last 20 years, and plastic cover, that lasts 8 years in MF (4 years in SP). For SP, tunnels contributed 34%, fertiliser 16%, seedling production 15% (mainly for greenhouse heating at the nursery), field emissions 11% and plastic 10% (mainly water pipes and mulch). For OP, diesel was the main contributor (54%) due to tractor use, before field emissions (34%).

Regarding CC, the three farms showed contrasting environmental profiles. This suggests different hints for eco- or re-design of the farms and calls for individualised consideration.

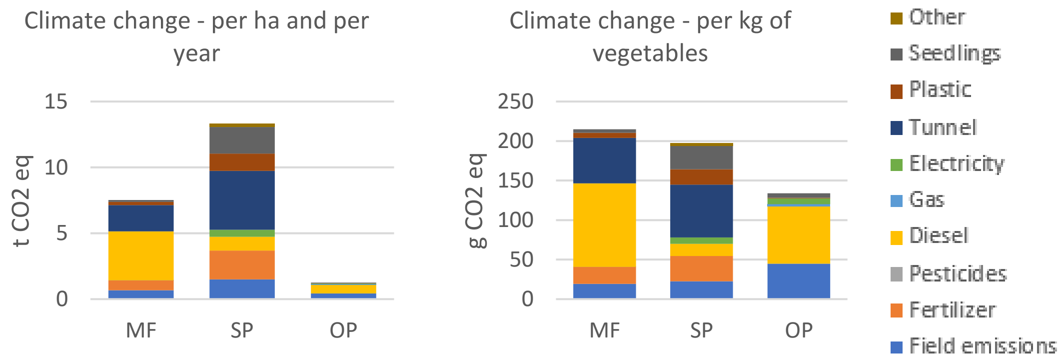


**Fig. 1. Impacts per ha of farmland during one year and per kg of vegetables; and contributions of inputs and field emissions for microfarm (MF), sheltered production farm (SP) and outdoor production farm (OP).**

## 3.2. Land competition

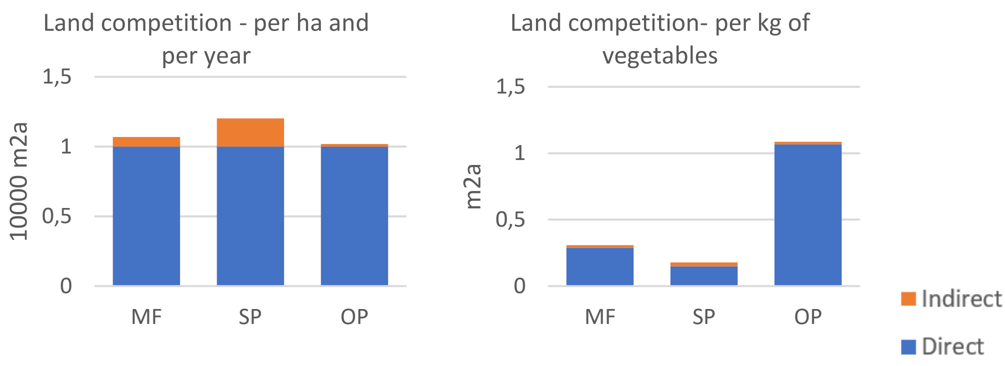


**Fig. 2. Impacts per ha of farmland during one year and per kg of vegetables; and contributions for microfarm (MF), sheltered production farm (SP) and outdoor production farm (OP).**

The environmental impact for LC of the three farms differed according to the functional unit. Per ha of land, the three farms have very similar impact on LC. They have little indirect land, i.e. off-farm land used for input production or transport. Per kg of vegetable, the farms differed greatly. OP had the highest impact for LC (1.07 $m^2a/kg$) followed by MF (0.29 $m^2a/kg$) and SP (0.15 $m^2a/kg$). OP has one cycle of crops per year and lower yields, thus it needs more land than MF and SP to produce the same mass of vegetables.

There is a trade-off between climate change, for which OP has the highest impact, and land competition, where it has the lowest impact.

## 3.3. Plastic use

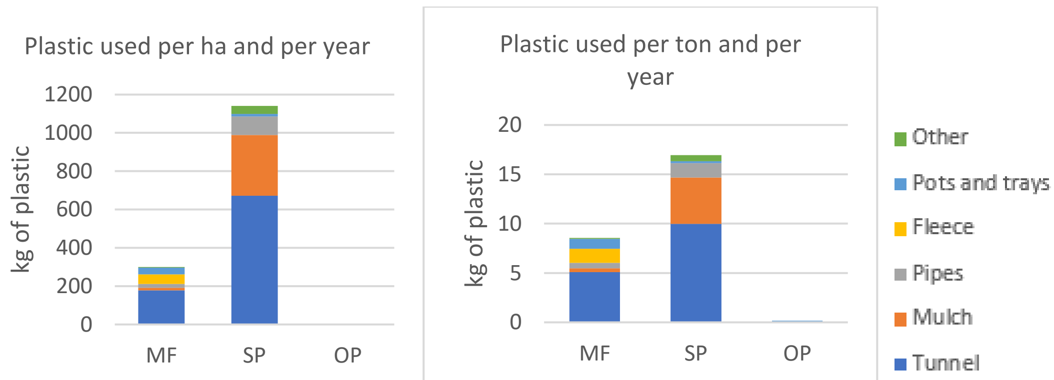


**Fig. 3. On-farm plastic use per ha of farm land and per t of vegetables; and contributions of plastic uses for microfarm (MF), sheltered production farm (SP) and outdoor production farm (OP).**

SP used two to four times more plastic depending on the functional unit (1129 kg/ha; 16.8 kg/t of vegetables) than MF (299 kg/ha; 8.5 kg/t of vegetables). OP used very little plastic (2 kg/ha; 0.2 kg/t of vegetables) (**Fig. *3***). Unlike CC and LC, the ranking of the farms is the same per ha and per kg. Plastic was mainly used in tunnels (60% of plastic use for MF and SP). SP used more plastic for the tunnel cover than MF for two reasons: 1) only part of the cultivated area of MF was under shelter, whereas all was under shelter in SP; 2) the plastic lifetime was 8 years in MF and 4 in SP. In MF the farmer repairs plastic as much as possible when damaged whereas in SP, the farmer changes the plastic automatically after four years to avoid risks of breaking. SP also used more plastic for mulching than MF and OP. In SP all crops were mulched with disposable plastic, whereas in MF straw mulching, manual weed control and reusable plastic mulch were combined.

The smaller size of MF allowed the farmer to repair damaged plastic and to handle and store reusable mulch and pipes. SP is too large to allow the farmer to do so, plastic is change according to a pre-established schedule in the case of the tunnel cover, or after every cycle of crop for mulch and pipes. It would be interesting to further study the influence of scale in the use of plastic.

Plastic pollution is an emerging and growing concern worldwide. The use of plastic in agriculture and the accumulation of microplastic in agricultural soil has been highlighted (United Nations Environment Programme, 2021). Vegetable crop production, including in organic farming, is a major user of plastic, particularly as mulch and tunnels for several purposes (e.g. earlier production, higher yield, weed control, cleaner vegetables) (Lamont, 2017, 2005), which is a threat to long-term soil quality (Steinmetz et al., 2016). Microplastics may have detrimental effects on plant growth (Liu et al., 2021), on soil properties (Zhang et al., n.d.), on the fitness of soil bacteria and earthworms (Jiang et al., 2020), and may be found in fruit and vegetables at worrying concentrations (Oliveri Conti et al., 2020). Massive use of plastic, especially in organic farming, has raised societal controversies (Held, 2019). However, there is no ready-made indicator in current LCA methods to assess plastic and microplastic pollution. Plastic use is not an LCA indicator, but it revealed major differences between farms. It is a first step towards considering the plastic issue in agriculture.

Recognising the long-term impacts of plastic particles is important to perform more reliable LCA studies (Gontard et al., 2022). It calls for the need to go beyond an indicator of plastic use and create impact indicator. Recent studies propose methods to create a new impact category for marine pollution by plastic waste, with different emission factors for different types of plastic (Lavoie et al., 2021; Saling et al., 2020; Woods et al., 2021).

## 3.4. Biodiversity

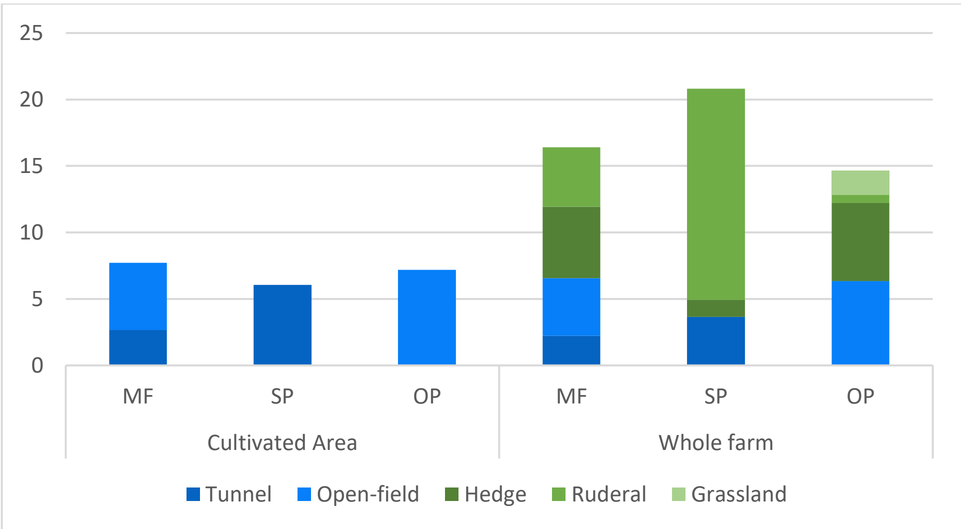


**Fig. 4. On-farm biodiversity scores (higher = better for biodiversity) and contributions of land-use types for microfarm (MF), sheltered production (SP) and outdoor production (OP).**
The scores are presented for the whole farm including cultivated land and semi-natural habitats, and for the cultivated land only. Blue bars represent cultivated areas, green bars represent semi-natural habitats.

For biodiversity scores (**Fig. *4***) the contribution of each land use type represents its intrinsic score, weighted by the proportion of the farm area it occupies. A large (a small, respectively) contribution can be due to a high (a low, respectively) intrinsic score or to the occupation of a large (a small, respectively) share of the farm or to a combination of both. Because of the weighting, the farm score is not an addition of the values for each land use type as for LCA indicators. For this reason, we display scores of the whole farms separately from scores of the cultivated areas. A high score indicates a high potential for biodiversity.

Considering cultivated areas alone, differences between farms were smaller (MF: 7.7, SP: 6.0 and OP: 7.2) than the differences for the scores for the whole farm, where SP had the highest score (20.8) with a contribution of 82% of the semi-natural habitats (in particular ruderal areas with 76%) and 18% of the tunnel. MF had a score of 16.4 with a balanced contribution of cultivated areas (40%) and semi-natural habitats (60%). OP had a score of 14.6, cultivated areas contributing for 43% and semi-natural habitats for 57%, including 40% due to hedges.

Assessing biodiversity on the cultivated part of the farm only or on the whole farm gave contrasting results, highlighting the importance of semi-natural habitats on a farm for biodiversity (Chiron et al., 2010; Jeanneret et al., 2021; Rischen et al., 2021). In SP, the cultivated area yielded a low biodiversity score, offset by the high proportion of ruderal area i.e. the spaces between the tunnels that are left to ruderal flora and fauna. In OP, fields were generally surrounded by a ruderal margin or a hedge. As the fields were large, the proportion of semi-natural habitat was lower, yielding a lower biodiversity score at farm scale. In MF the cultivated area yielded a comparable biodiversity score to the other systems. From a theoretical maximum score of 45 that can be obtained by semi-natural habitats such as hedgerows, biodiversity-friendly managed grasslands and pastures may reach a score of 25 (Lüscher et al., 2017) which is here the case of the SP grassland. Such scores are far higher than the vegetable fields under investigation here (6-8).

### 3.5. Farm-specific effect

Although we selected typical farms of different farming systems, we studied cases where farm-specific effects cannot be ignored. For example, MF used a diesel pump for irrigation, contributing strongly to climate change, whereas a lot of farms use electric pumps. In SP, ruderal areas between tunnels occupied a large proportion of the farm, but farms similar to SP use glasshouses or multispan greenhouses instead of tunnels, without inter-tunnel areas. OP reduced the use of plastic close to zero, but some farms growing vegetables on large areas outdoors like OP use plastic mulch or small plastic "caterpillar" tunnels.

## 4. Conclusion

The assessment of three contrasting farms with different functional units and impact categories did not show a clear ranking of the farms. The causes of impacts differ according to the categories: climate change and plastic are related to the inputs, land competition is related to the yield, and biodiversity is related to semi-natural areas and field size. Designing farming systems with a low environmental impact imply finding the best trade-off.

The three farms produce different types of vegetables and sell to different markets, they have complementary functions. The results highlight different environmental profiles and inform on how the farms respond to different environmental issues. Instead of opposing the farming models, it brings information to the decision makers to find the best balance between farms according to environmental priorities.

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