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Energy consumption and efficiency in vegetable farming systems: Is saving energy or sparing land the priority?

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Abstract: Yield, defined as the mass of product per unit area, is central in the assessment of agricultural performances. The implicit assumption behind the importance of yield is that land is the main limiting factor to produce food. But energy could become a new limiting factor that we should consider for assessing the performance of emerging farming systems. We compared vegetable production systems including outdoor production, greenhouses and plant factories. Our results show contrasting levels of energy consumption and annual dry matter yields. Yield increases as energy input increases, which indicates that land and energy inputs are substitutable. However, energy use efficiency decreases as energy input increases, hereby challenging the promises of high-tech production. The implications are (1) the need of considering energy use efficiency in addition to (area-based) yield when assessing the performances of farming systems, (2) the need of tackling the food system transition with the farming system transition, and (3) that 'area-extensive' farming systems can be very energy use efficient, thus being promising transition pathways.

Keywords: Yield, energy, vegetable production, land

Purpose

Yield, defined as the mass of product per unit area, is central in the assessment of the performances of agricultural systems (e.g. Burchfield and Nelson, 2021; Lesur-Dumoulin et al., 2017; Lobell et al., 2009). The implicit assumption behind the importance of yield is that land is the main limiting factor to produce food. Indeed, a farmer, a country and the world has a limited agricultural area, where it matters to produce a satisfactory amount of food, especially as the world's population increases. In the industrial era, considerable efforts were made to increase yields, notably through the development of fertilisers, machinery, irrigation, pesticides and genetics (Harchaoui and Chatzimpiros, 2019). However, these efforts were made in a world where energy was relatively cheap and abundant. The world is now facing a new situation where energy is getting increasingly expensive, scarce, and uncertain (Dittmar, 2013; Kaufmann, 2014; Patterson and Perl, 2007). As for land, energy could become a new limiting factor that we should consider for assessing the performance of emerging farming systems (Martin et al., 2023).

Vegetable production systems present major variability in production technologies, including outdoor production, greenhouse cultivation (heated or not), and plant factories (i.e. soilless, fully-closed controlled systems relying on artificial lights, also called 'vertical farms'). In this paper, we explore the relation between (area-based) yield and energy efficiency of contrasting vegetable farming systems, including emerging farming systems, using a life cycle approach.

Design/Methodology/Approach

We used the life cycle assessment (LCA) framework to assess the cumulative energy demand (CED) (Frischknecht et al., 2015) of three organic vegetable farms in France : a microfarm producing outdoors and in an unheated greenhouse, a farm specialised in sheltered (unheated) production and a large open-field farm. They were assessed in a farming system approach, i.e. all inputs and operations were estimated for the entire farm, and the output was the total production of vegetables. The data of the three case study farms were collected through interviews. We used the Ecoinvent database for indirect energy (i.e. energy used in the production of inputs and infrastructure). We considered both renewable and non-renewable energy for growing the vegetables, excluding energy captured by photosynthesis. We used the CIQUAL database (https://ciqual.anses.fr/) for the dry matter and energy content of the vegetables.

We compared these three farms to other vegetable production systems from the literature, including conventional open-field, heated greenhouse with or without energy saving systems, including winter production, and vertical farming. The energy input in Ntinas et al. (2017) was calculated using CED (Frischknecht et al., 2015). (Graamans et al., 2018) calculated the energetic loads including artificial illumination by LED, LED cooling, sensible cooling, dehumidification, heating and installed power. It excluded the background system energy demand, i.e. energy used to produce fertilisers, pesticides and infrastructure. This indirect energy use account for 12.4 to 13.4% of the CED in similar systems of Ntinas et al. (2017), which gives an approximation of the underestimation of the energy values of Graamans et al. (2018).

The (area-based) yield was expressed as dry matter mass produced per unit of area. The energy use efficiency was expressed as Energy Return On Investment (EROI), calculated as EROI = energy in vegetables produced / energy input.

Findings

The vegetable farming systems had contrasting levels of energy consumption (from 29 to 70 900 $GJ.ha^{-1} yr^{-1}$) and annual dry matter yield (from 1.2 to 50 t $DM.ha^{-1} yr^{-1}$) (*Table 1*). Yield increased as energy input increased (i.e. producing a given quantity of vegetables required less land as energy input increased), which indicates that land and energy inputs are substitutable. However, energy use efficiency, expressed as EROI, decreased as energy input increased, from ca. 1 for outdoor conventional and organic production to 0.01 for a plant factory. The outdoor systems produced 72.7 kg DM per GJ invested (i.e. the equivalent of 1 L of fuel produced 32 kg of fresh vegetables). The plant factory produced 0.7 kg DM per GJ invested (i.e. the equivalent of 1 L of fuel produced 0.4 kg of fresh vegetables).

Table 1. Product, energy input, yield, energy output, and energy return on investment (EROI) of contrasting vegetable production systems

System	**Product**	**Energy input (E_{in}, GJ.ha^{-1}.yr^{-1})**	**(area-based) Yield (t DM.ha^{-1}.yr^{-1})**	**Energy-based yield (kg DM.GJ^{-1})**	**Energy output (E_{out}, GJ.ha^{-1}.yr^{-1})**	**EROI (E_{out}/E_{in})**	**Source**
Organic, outdoor, France	Mix of vegetables	29	1,2	42,1	19	0,640	Pépin et al., 2022
Conventional, outdoor, Greece	Industrial tomato	103	7,5	72,7	103	1,000	Ntinas et al., 2017
Organic, outdoor/unheated greenhouse, France	Mix of vegetables	157	3,1	19,5	45	0,285	Pépin et al., 2022
Conventional, outdoor, Greece	Fresh tomato	275	2,4	8,6	32	0,118	Ntinas et al., 2017
Organic, unheated greenhouse, France	Mix of vegetables	387	3,4	8,8	49	0,126	Pépin et al., 2022
Conventional, soil, heated greenhouse with Energy Saving System, Germany	Fresh tomato	3981	10,6	2,7	145	0,036	Ntinas et al., 2017
Conventional, soil, heated greenhouse, Germany	Fresh tomato	6809	8,7	1,3	119	0,018	Ntinas et al., 2017
Conventional, in winter, soilless, heated greenhouse with Energy Saving System, Greece	Fresh tomato	7155	3,8	0,5	53	0,007	Ntinas et al., 2017
Conventional, in winter, soilless, heated greenhouse, Greece	Fresh tomato	8507	3,4	0,4	47	0,006	Ntinas et al., 2017
Conventional, soilless, greenhouse, Netherlands	Lettuce	12100	21,0	1,7	297	0,025	Graamans et al., 2018
Conventional, plant factory, Netherlands	Lettuce	70900	50,0	0,7	706	0,010	Graamans et al., 2018

Implications

Vertical farming is often seen as a solution to feed the growing global population by increasing resource and land-use efficiency (Csordás and Füzesi, 2023), and in the near future as an alternative agricultural production system in complement to traditional agriculture (Zaręba et al., 2021). Indeed, its (area-based) yield was 7 to 42 times higher than that of outdoor cropping, and 2 to 15 times higher than production in greenhouses. This optimism regarding high-tech solutions to feed the world is challenged by their very low energy use efficiency. Despite slightly better values for EROI, heated greenhouse systems also had a very low energy use efficiency. Energy saving systems, such as insulated greenhouses, allow lower energy use for similar (area-based) yield, resulting in higher energy use efficiency compared to classic heated greenhouses, but still lower efficiency compared to unheated systems.

Considering that the use of both land and energy are critical points of a transition towards more sustainable farming systems, there is a major challenge to develop systems with satisfactory yields and a limited energy use. In this perspective, the (area-based) yield should not be looked at without energy efficiency indicators, such as EROI or the energy-based yield (i.e. the quantity produced per energy invested) in order to find the best trade-offs.

The heated greenhouse systems that produce tomatoes in winter had a lower energy use efficiency than other heated greenhouse systems, due to the high need of energy to heat the crops and the relatively low yields. This calls for reconsidering the demand of tomatoes in winter and shows that the transition of the farming systems is connected to the transition of the food system (Martin et al., 2023).

Farming systems with outdoor production or in unheated greenhouses may seem to have unsatisfactory yields compared to the most productive heated greenhouses or plant factories, but they need little energy to produce and are more energy efficient. In a context where energy becomes more expensive, scarce while still contributing to climate change, those low-tech systems, including small organic farming, may be promising transition pathways, calling for more research and development effort in this direction (Gaitan-Cremaschi et al., 2020).

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