RESEARCH ARTICLE

A life-cycle approach highlights the nutritional and environmental superiority of agroecology over conventional farming: A case study of a Mediterranean farm

Alik Pelman[1]*, **Jerke W. De Vries**[2], **Sigal Tepper**[3], **Gidon Eshel**[4], **Yohay Carmel**[5], **Alon Shepon**[6]

1 Department of Humanities and Arts, The Technion-Israel Institute of Technology, Haifa, Israel, **2** Applied Research Centre, VHL University of Applied Sciences, Velp, Netherlands, **3** Department of Nutritional Sciences, Tel-Hai College, Tel Hai, Israel, **4** Physics Department, Bard College, Annandale-on-Hudson, New York, United States of America, **5** Faculty of Civil and Environmental Engineering, The Technion-Israel Institute of Technology, Haifa, Israel, **6** The Porter School of the Environment and Earth Sciences, Tel Aviv University, Tel Aviv, Israel

* alikpelman@technion.ac.il

OPEN ACCESS

Citation: Pelman A, De Vries JW, Tepper S, Eshel G, Carmel Y, Shepon A (2024) A life-cycle approach highlights the nutritional and environmental superiority of agroecology over conventional farming: A case study of a Mediterranean farm. PLOS Sustain Transform 3(6): e0000066. https://doi.org/10.1371/journal.pstr.0000066

Editor: Lian Pin Koh, National University of Singapore, SINGAPORE

Received: April 28, 2023

Accepted: May 29, 2024

Published: June 28, 2024

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pstr.0000066

Abstract

Providing equitable food security for a growing population while minimizing environmental impacts and enhancing resilience to climate shocks is an ongoing challenge. Here, we quantify the resource intensity, environmental impacts and nutritional output of a small (0.075 ha) low-input subsistence Mediterranean agroecological farm in a developed nation that is based on intercropping and annual crop rotation. The farm provides one individual, the proprietor, with nutritional self-sufficiency (adequate intake of an array of macro- and micronutrients) with limited labor, no synthetic fertilizers or herbicides, and zero waste, effectively closing a full farm-table-farm cycle. We find that the agroecological farm outperforms conventional farming as practiced in the same country in terms of both lower environmental burdens, across all examined environmental metrics (63% lower on average) per kg produce, and higher nutritional score (66% higher on average). Per equal farmland, the environmental lopsidedness was even higher (79% lower than conventional farming on average), with nearly the same nutritional score (3% lower on average). Moreover, when considering total land area, which includes farmland and supporting non-agricultural lands, as well as post-gate impacts and food losses, the advantage of the agroecological system over conventional farming is even more pronounced. Situated within a Mediterranean region that is undergoing rapid climate change, this food system is a unique case study of nutrition- and environment-oriented food production system. While its deployment potential is limited by lack of supportive policies, it nonetheless represents one of the most starkly bold alternatives to current food systems.

Data Availability Statement: All code and datasets appear in the following public repository: https://github.com/alonshepon/agroecological_farm.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Author summary

The transition to sustainable food systems is now recognized by governments and international organizations as central to achieving the sustainable development goals (SDGs) and adhering to the commitments of the Paris agreement on climate change. Many studies have highlighted the transformative potential of agroecology, but these efforts are still handicapped by insufficient empirical data. In our study, we evaluated key nutritional as well as environmental outputs of a small self-sufficient Mediterranean agroecological farm and compared them to the conventional farming practiced in the same country. We found that the 0.074 ha agroecological farm meets self sufficiency of an adult male in all macro- and micro-nutrients save for calcium. The farm outperforms conventional farming in terms of both lower environmental burdens (63% lower on average) per kg produce, and higher nutritional score (66% higher on average). Per equal land area, the environmental lopsidedness was even higher (79% lower than conventional farming on average), with nearly the same nutritional output (3% lower on average). Moreover, when considering total land area, which includes farmland and supporting non-agricultural lands, as well as postgate impacts and food losses, the advantage of the agroecological system over conventional farming is even more pronounced. Our results clearly highlight the currently untapped potential of agroecological farms to enhance nutritional security while minimizing environmental impacts.

1. Introduction

Given the large impact of food systems on natural environments and human society, the transition to sustainable food systems is now recognized by governments and international organizations as central to achieving the sustainable development goals (SDGs) and adhering to the commitments of the Paris agreement on climate change [1]. Various strategies for food system transformation have been proposed in recent years. On the supply side, they include alternative agricultural practices that promote soil conservation, low input agriculture, carbon enhancement through the reduction of emissions of greenhouse gases (GHGs), enhanced sequestration in agricultural soils, and increased agrobiodiversity [2,3]. On the demand side, proposed alternatives stress the retail and consumer side of the food system that improve the food environment and promote access to, and consumption of, healthy foods while reducing food waste, through information (e.g., environmental labeling [4]), education [5], and institutions and policies [6]). Others highlight the importance of reducing corporate control [7] and unequal access to food, while enhancing inclusivity in decision making and food sovereignty [8].

Many studies have highlighted the transformative potential of agroecology to food systems [9], especially its capacity to promote multiple of the above transformational objectives simultaneously. Agroecology refers to changing agricultural landscapes into biodiverse, nutrient rich landscapes that mimic natural processes and ecosystems, employing mostly small farms. However, since its inception as a scientific discipline, agroecology has matured into a social movement that openly challenges industrial agricultural production and rural development [10]. Recently, the Intergovernmental Panel on Climate Change (IPCC) has recognized agroecology as a transformative climate change strategy that strengthens resilience [11], biodiversity [12], and nutritional security [13].

Not surprisingly, a large and rapidly burgeoning body of literature has examined various dimensions of agroecology since the 1980s, focusing on enhancing ecological conservation, biodiversity, and sustainability of agricultural practices used in production of crops and livestock [10]. In recent years, agroecology research has veered also toward focusing on ecosystem services [14], social justice [15], economic, racial, and gender equity [16], community connectivity and resilience [17], and policy and governance [18] that are needed to maximize sustainability of entire food systems [19].

Life cycle assessment (LCA) is currently the most comprehensive tool available for environmental assessment of (food) systems [20]. LCAs are used for quantifying the environmental impacts of various food items, food groups, environmental categories [21], and agricultural production practices [22]. They reveal that shifts from animal-based to plant-based foods provide large environmental benefits across multiple impact categories, more than shifting from conventional to organic production. Yet, LCAs are often limited by solely focussing on production (biomass output) and comparing relatively few impact categories (e.g. GHG and land occupation), thus imperfectly capturing agriculture's multifunctionality, land use, and provision of other positive impacts on, e.g., ecosystem services.

In terms of nutrition, a recent review [23] has concluded that in most cases, agroecological practices such as crop diversification and soil management enhance food security and nutrition. Likewise, practices of intercropping—which are common in small-scale farming like agroecology—have been recently shown to lead to significant land saving relative to growing the same crops on separate plots, in addition to providing other ecological services [24].

Yet, to date, research efforts are still handicapped by insufficient empirical data on the performance of small-scale agroecological farms, and on how soil, climate, and agronomic conditions affect farm performance [25]. LCAs of agroecological practices are lacking too. Because of the focus on high yields, and limited attention to environmental impact and nutrient content differences among food groups and production systems [26], intensive agriculture enjoys an artificial edge over agroecological practices in LCA studies. When applying LCA to agroecological practices, therefore, more impact categories should be included and attention should be given to multiple functional units including land-based units instead of production-based units only. Moreover, the nutritional benefits of agroecology [27,28] are mostly overlooked in research, yet are essential to evaluating agriculture's contribution to health and as an impetus for transforming food systems through expanding agroecological farming [28].

To bridge the above knowledge gaps, we complemented an extended environmental examination of an agroecological smallholder farm with a nutritional analysis and compared it to conventional agriculture based on its produce and land use. Specifically, we analyzed a 0.074 hectare self-sufficient Mediterranean agroecological farm in northern Israel using LCA, and evaluated key macro- and micro- nutrients critical to human health in the farm's output, and then compared them to both the corresponding requirements of the farm proprietor and to the mean nutritional supply by Israeli conventional agriculture. Our approach overcomes LCA's shortcomings by considering not only mass produced but also area-occupied functional units, and by considering additional impact categories, thereby enabling an examination of the environmental-nutritional performance of both agricultural systems. Although our study addresses a single system, and thus yields deterministic rather than statistical conclusions, it clearly highlights the untapped potential of agroecological farms to enhance nutritional security while minimizing environmental impacts.

2. Methods

2.1 Study systems

2.1.1 Agroecological system. The smallholder farm is sited in the western Galilee, northern Israel, at 130 m above sea level, under typical northern Mediterranean climate with an annual mean precipitation of ≈700 mm y^{-1}, with day/night temperatures of 30˚/20˚C in summer and 20˚/10˚C in winter. The total farm size is 0.2 hectares, of which 740 m^2 (0.074 ha) are used for food production. Wheat and fava beans are sown in December and harvested in June, on 200 m^2 and 350 m^2, respectively. Seasonal vegetables are grown year round in a 140 m^2 vegetable garden. Nine olive trees are harvested in November, and one carob tree is harvested in August. The field crops are grown almost clear to the trees' trunks, therefore net cover of the ten trees is relatively small (50 m^2). Lastly, honey is harvested in July, from one beehive that occupies 1 m^2, which also improves pollination.

The agroecological farm strives to deliver a complete balanced diet to the producing farmer with minimum environmental burdens (see Results section and supporting information), and thus its resultant diet derives most of its macronutrients from wheat, fava beans and olive oil. These crops are all completely rainfed, have relatively high nutritional yields, store well year round, requiring little, unrefrigerated, storage space, and are local varieties requiring no synthetic chemicals and very little compost fertilization. These three crops jointly occupy about 600 m^2, some 80% of the farm area, accompanying the 140 m^2 irrigated vegetable garden. No transportation and packaging are required and the localized food system can be considered a "zero waste" system (see section 3.1 for details).

Produce harvest occurs year round, with wheat and fava alternating locations in a two-year crop rotation. In early December, the wheat and fava plot is tilled with a small tractor, leaving it weed-free. Then, wheat and fava seeds are broadcast manually, and covered with soil with another round of the tractor. In early April, the plot is electric-fenced against wild boar. In late May, when the wheat and fava beans are entirely dry, both are manually harvested with a sickle, and the fence is removed. Lastly, both crops are threshed using a small petrol-powered threshing machine, and the seeds are stored for the whole year. In early November, about 160 kg olives are picked with a small electric harvester and are taken to a traditional oil press in a nearby village. The resulting ≈40 kg of oil are stored at home in a stainless steel container for year-round consumption.

The 140 m^2 vegetable garden yields some 40 different vegetables. In order to have a steady flow of produce, crops are being planted on a monthly basis, 8 months a year, September-November plus February with winter crops, and March-June with summer crops. During each of the above 8 months, 25% of the garden (35 m^2) is being planted, with each given location planted once in winter and once in summer. To maintain soil health, a 9-year crop-rotation cycle is maintained, with a given crop reoccupying the same location every 9 years (see 'vegetable garden plan' spreadsheet in S1 Data, for a detailed multi-year plan). Vegetables are grown organically (i.e., chemical-free), and seasonally (i.e., no polytunnels etc.), with approximately 20 and 15 varieties over the winter and summer, respectively. The garden is the only irrigated plot, with 0–3 automatically controlled hours of drip irrigation per week, varying seasonally.

One beehive is located at the edge of the farm. It is inspected once every 1–2 months. In July, about 15 kg of honey are harvested (about 6–7 of the 19 honeycombs), leaving about 10 kg of honey in the hive. Bees are not fed with any sugar syrup (unlike the common practice of conventional or organic beekeeping). Honey extraction is purely gravitational.

2.1.2 Conventional farming systems. To assess the environmental performance of the agroecological farm (hereafter, AGRO), and its nutritional delivery, we compared it to the performance of two alternative agricultural systems. The first, denoted as business as usual (BAU), details present agricultural production methods in Israel with its unique crop mix. The other, denoted as MIX, is a hypothetical agricultural system that produces the exact harvest and crop mix as the AGRO but under conventional Israeli yields and production methods. Comparing AGRO to MIX highlights the impacts of agricultural practices of a given crop assemblage on environmental performance, while comparing MIX to BAU highlights the effects of alternating crop assemblages on diet quality and environmental performance.

The comparison of these systems was conducted separately on an equal mass basis and on equal land (farm size) basis. In the comparison on an equal mass basis, total production in Israel (BAU) was normalized to the farm produce, in kilograms, thus comparing the environmental and nutritional performance of all three systems on an equal mass basis. In the comparison on an equal land basis, MIX and BAU outputs were normalized to the size of the AGRO farm in m^2, thus comparing the environmental and nutritional performance of all systems on an equal land basis. We compare the environmental and nutritional characteristics of the three systems in sections 3.4.1 and 3.4.2.

The available data regarding the conventional farming areas in Israel (BAU) aggregates the area occupied by each crop, taking note of same-year crop rotation (i.e., growing two or more crops on the same plot in the same year). In such cases, land area is counted twice. Accordingly, the total farmed area is indicated in units of m^2a (i.e., area time). For consistency and a proper comparison, we applied a similar calculation to the agroecological farm (AGRO). Each of the wheat, fava beans, and olive oil plots produces one crop per year—totalling 600 m^2—whereas each area in the 140 m^2 vegetable garden produces two crops per year (apart from a small section of 18 m^2 that is used for green manure over the winter). Thus, the total area of the vegetable garden was calculated to be 262 m^2a (i.e., 140 m^2 + 140 m^2–18 m^2) and, accordingly, the farm land area was taken to be 863 m^2a (i.e., 741 m^2 + 140 m^2–18 m^2). (See, 'harvest' spreadsheet in S1 Data).

2.2 Data collection and analysis

2.2.1 Nutritional analysis. We conducted a nutrient content analysis based on weekly harvest of vegetables and the annual harvest of fava, wheat, olive oil, honey and carob. Nutritional supply is the product of harvest mass and the corresponding nutritional content, i.e., nutrients per unit mass. The detailed monthly harvest data is provided in S1 Data (see 'harvest' spreadsheet). We obtained national level agricultural harvest from Toperoff et al [30] and data from the Israeli Plants Production and Marketing Board [31], and information on carbohydrates, fat, protein, calories, zinc, iron, calcium, and magnesium from the Israeli food and nutrient database using the Tzameret software, developed by the Israeli ministry of health [32] (see S1 Appendix, Section 2, for more details). Since various agricultural and climatic factors can affect the nutritional content of crops, we collected crop samples and analyzed them in the laboratory. We found that the resultant values closely resembled the nationally representative values of the Tzameret database.

The nutritional content analysis considers and corrects for waste where appropriate by focusing only on the edible portions of relevant food items. For instance, the database includes entries for whole corn (including cob and leaves), corn (kernels with the cob), and just corn kernels. For the nutritional calculations, we use the corn kernels after adjusting for kernel fraction in total mass. Since most fruits, vegetables, and tubers are consumed in their entirety, we use the unpeeled items' information. We thus accurately represent the edible portion of each food item.

Given that the farm has zero waste, the average daily nutrient supply is the nutrient content of the annual production of wheat, fava, oil, seasonal vegetables, honey and carob divided by days in a year (recasting harvest period availability as per day equivalent). We aggregated harvests into seven food groups: cereal, legumes, vegetables, fruits, sugar, oil, and tubers. Nutrient sufficiency is quantified by expressing the above nutrient outputs as percentages of the Recommended Dietary Allowance (RDA) or Adequate Intake (AI) of a 70 kg male adult. AI/RDA are

Table 1. RDAs and AIs per person used in the nutritional analysis.

	Energy (kcal d^{-1})	Protein (gr d^{-1})	Total fat (gr d^{-1})	Carbohydrates (gr d^{-1})	Calcium (mg d^{-1})	Iron (mg d^{-1})	Magnesium (mg d^{-1})	Zinc (mg d^{-1})
RDA/AI	2180	56	73	130	1000	8	420	8

https://doi.org/10.1371/journal.pstr.0000066.t001

reference individual intakes that meet the needs of 97–98% of the population (Table 1) [32]. Nutrient sufficiency values below and above 100% denote deficiency and sufficiency, respectively. Since total fat RDA/AI have not been established, we used the acceptable macronutrient distribution range (AMDR), with fat accounting for 20–35% of energy, and set the sufficiency threshold at 30% of energy intake (or 73 g for 2200 kcal when using 9 kcal g^{-1} for fat). We also calculated saturated, poly- and mono-unsaturated fats, and linolenic and linoleic fatty acid proportions of total fat.

We then compared the nutritional output of the agroecological farm (AGRO) to that of the two alternative agricultural systems (BAU and MIX). We compared the differences in nutritional supply of these systems for each of the above macro- and micronutrients individually, and in terms of a relative nutritional score that is the average nutrient supply of all the eight examined nutrients relative to BAU (see 'Comparative Analysis' spreadsheet in S1 Data). Such relative nutritional scores below or above 100% indicate that examined systems are nutritionally inferior or superior to the BAU system in terms of nutritional quality.

2.2.2 Environmental analysis. LCA was used to compare the environmental performance of the AGRO, MIX and BAU systems up to farm gate. We considered the following nine expanded impact categories in order to capture as many aspects as possible related to agroecological production [26]: greenhouse gasses (kg CO_2-eq), marine eutrophication (kg N-eq), terrestrial acidification (kg SO_2-eq), blue water use (m^3), fossil energy use (MJ), land occupation (m^2a), ecotoxicity (comparative toxic units or CTUe), human toxicity (CTUh), and biodiversity loss (species•y). We modeled all environmental impacts, except toxicity, following the ReCiPe midpoint hierarchist impact assessment method [33], using century scale global warming. Toxicity was inventoried according to the USEtox methodology [34].

2.2.3 Functional unit and system boundaries. The functional unit is the unit output of the production system or the service provided. Because our objective here is to compare the AGRO farm, that is, agroecological production, to conventional agricultural production in the same country (MIX or BAU), we used two functional units in all three systems. The first is the total annual output of the agroecological farm (AGRO), which is 728 kg of produce annually, and the second is the farm's agricultural area, which is 863 m^2a.

The system boundaries we used include all processes needed to produce the farm's output at the farm gate, i.e. 'cradle to farmgate.' Importantly, this includes production of such input materials as compost (whose transport to the farm is included), various fuels, or electric energy (Fig 1). Table 2 provides a detailed account of the inputs of the agroecological farm (including fuels, irrigation, compost). In the conventional agriculture scenarios, namely MIX or BAU, production of conventional inputs such as mineral fertilizer and herbicides/pesticides are also included.

2.2.4 Data acquisition, main assumptions and processing. We obtained and analyzed data from the agroecological farm, acquired over several years of stable operation. The data include the production of vegetables, wheat and other crops, as well as the use of fuel, compost, and irrigation water. Emissions and resource-use due to the production and use of various fuels, misc. materials, compost, and irrigation were included. The data used for the LCA includes the Ecoinvent database, version 3.2 with substitution [35] and relevant literature, as described in more details in Table I and Table J in S1 Appendix. Our key assumptions follow, with further details provided in S1 Appendix.

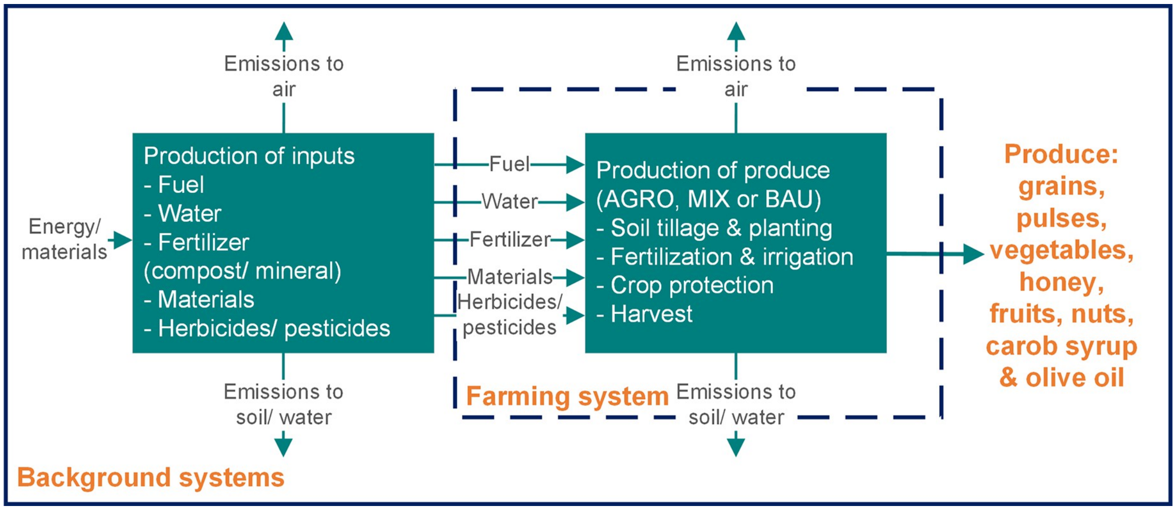

Fig 1. System definition and boundaries, including the production of inputs (fuel, fertilizer, materials, as well as herbicides, and pesticides) to produce the annual produce: grains, pulses, vegetables, honey, carob syrup, olive oil, fruits and nuts. Upstream (background) and on-farm resource usage and environmental impacts are included. Post-farmgate environmental impacts (e.g., processing or transport to consumers) are excluded. For simplicity, transport between processes is not shown.

https://doi.org/10.1371/journal.pstr.0000066.g001

Emissions of nitrous oxide (N_2O), methane (CH_4) and ammonia (NH_3) related to compost production (based on a meta-analysis of cattle manure composting [36] (Table H in S1 Appendix) are 280 g N_2O kg^{-1}, 3.4 g CH_4 kg^{-1} and 1.2 g NH_3 kg^{-1}, respectively. We assumed composting requires 29 kWh ton^{-1} [37]. As the emissions from composting vary considerably, we also envisioned an alternative, based on assuming municipal solid waste composting (see 'LCA' spreadsheet in S1 Data). This yielded 0.1 g N_2O kg^{-1}, 0.2 g CH_4 kg^{-1} and 0.03 g NH_3 kg^{-1} [37].

We considered compost (with density of 599 kg m^{-3} [38] and transportation of 30 km (the distance to the local processing plant), with emissions modeled based on a Lorry Euro 5 weighing >32 tons [35]. Because compost application is done manually in the agroecological farm, it incurs no emissions. However, emissions of N_2O (1.25% of total applied N), NH_3 (5.75% of total ammoniacal N (TAN), which is itself 5% of total N), nitrogen oxide (NO, 0.55% of N) and nitrate (NO_3^-, 27% of N) from compost application are included using the IPCC guidelines and De Vries et al. [39]. Carbon (C) sequestration from applying compost to the soil is included at a rate of 715 kg C ha^{-1} y^{-1} or 2620 kg CO_2 ha^{-1} y^{-1} based on published synthesis of C sequestration data [40]. Compost application increases water retention in the soil, thus reducing irrigation needs, whose magnitude we assume is 2.4%, which translates to 2.4% water saving [41].

Carbon emissions averted by reduced soil tillage are credited to wheat and fava bean plots, whose tilling is shallow, forgoing inversion, at a rate of 500 kg CO_2-C ha^{-1} y^{-1} based on the mean difference between conventional and reduced/minimum tillage in the USA and

Table 2. On-farm annual inputs for production per food groups (outputs).

	Vegetables	Olives	Pulses	Wheat	Honey	Total
Plot size (m^2)	140	50	350	200	1	**741**
Irrigation (m^3)	50	-	-	-	-	**50**
Fuel (liters)	10	-	14	9		**33**
Compost (m^3)	3	1	-	-		**4**

https://doi.org/10.1371/journal.pstr.0000066.t002

Morocco [42]. This credit totals 1780 kg CO_2 ha^{-1} y^{-1}. Nitrogen (N), phosphorus (P) and potassium (K), the main agricultural nutrients, are delivered through compost and fava bean N fixing, substituting mineral fertilizer and averting the emissions associated with its production and application. To quantify this, we used an N fertilizer replacement value (NFRV) of 15% for compost N replacing synthetic N, with an N content for compost of 5 g kg^{-1} [38], and 60% for fixed N.

The materials used in capital goods like power tiller and string trimmer were included and assumed to be metal. The machinery was assumed to have an average life span of 10 years and to be used for food production 50% of the time. Emissions associated with metal manufacturing were included, using values from the Ecoinvent database [35].

2.3 Data limitations and uncertainties in LCA

Most uncertainties in the data for the AGRO scenario were related to compost production and use, while the main uncertainty sources in the MIX and BAU scenarios were differences in olive oil yield between the original data (based on world average sources) and the Israeli yield data [29]. We tested the effect of these uncertainties on the end results as follows. For compost production, we produced an alternative scenario, based on composting of municipal solid waste. To further examine sensitivity to Israeli (lower) yields, we also applied global mean yields in the MIX and BAU scenarios (see 'LCA' spreadsheet in S1 Data). We also tested the sensitivities of the results to changes in olive oil yield by reducing the empirical value (in the original data source) of 2500 kg ha^{-1} to 1000 kg ha^{-1}, and by replacing mean GHG emissions with their lower-bound, i.e. 1.2 kg CO_2-eq per kg oil.

3. Results

3.1 Farm inputs

Ongoing inputs invested in producing food on the farm include water for irrigation, fuel for small power tools and tractor, and compost as fertilizer. Wheat, fava beans and olives grow using only rainfall, so no irrigation is used. The vegetable garden is irrigated in the dry months, between March-November requiring an estimated 50 m^3 of water annually. Performing farm work is aided by four small power tools: a string trimmer, power tiller, threshing machine (all run on petrol fuel), electric olive harvester (connected to the farm's solar power system), as well as a diesel tractor hired for 2 hours a year (for tilling before annual sowing of wheat and fava beans). Total time of using the tools annually is estimated at 21 hours with a fuel usage of about 33 liters annually. In addition, our LCA calculus includes a monthly 30 km journey (each direction) by car to the nursery and gardening shop for seedlings and supplies. Crop cultivation on the farm does not necessitate synthetic inputs including pesticides, herbicides, synthetic fertilizer, plant growth regulators, or nanomaterials. The vegetable plot uses 10 liters of organic compost for fertilization per 1 m^2, i.e., 1400 liters for the entire plot, twice a year (winter and summer), totalling about 3 m^3 of purchased compost annually for the vegetable garden. Olive trees are fertilized once a year before the rainy season with about 100 liters for each tree of compost produced onsite (1 m^3 of compost for all 9 trees). All in all, 4 m^3 of compost are being used as fertilizer on the farm annually (see Table 2).

3.2 Farm produce

On average, the farm's 740 m^2 of cultivated area produces an annual total of 728 kg of crops, composed of 48, 84, 40, 536, 15, 5 kgs of wheat, pulses, olive oil, seasonal vegetables, honey, and carob syrup, respectively. Fig 2 presents the monthly harvest per food group across a

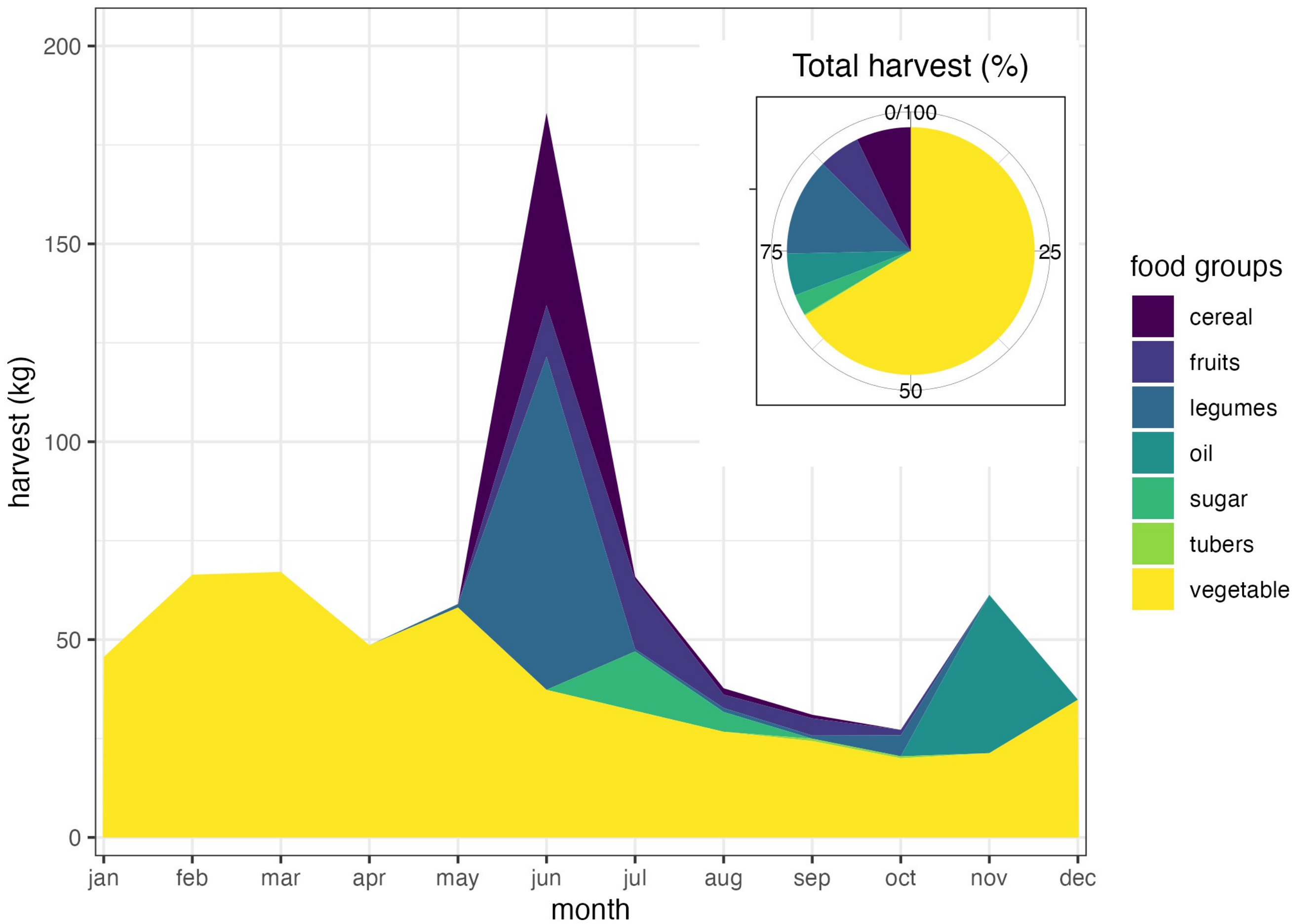

Fig 2. Harvest (in kg) by food group and month on the agroecological farm (AGRO). The inset presents relative food group contributions to the total farm mass output.

https://doi.org/10.1371/journal.pstr.0000066.g002

typical year (see 'harvest' spreadsheet in S1 Data, for more detailed information). Although wheat, fava, and olives are harvested once a year, they are stored and consumed evenly year-round. The same holds for honey and carob (turned into syrup). In contrast, vegetables are picked every couple of days and are eaten within a few days. By mass, vegetables constitute about 68% of total harvest, followed by legumes (12%), cereals (6%), fruits (5%—consisting of watermelons and melons), oil (5%), sugar (3%—consisting of honey and carob), and tubers (<1%).

3.3 Nutritional supply

Table 3 lists the average daily nutritional values produced on the agroecological farm (for more detailed information, see 'daily nutrients production' spreadsheet in S1 Data). Fig 3 presents the monthly nutritional supply of total farm output by food group. Most values are

Table 3. Average daily nutritional values produced on the agroecological farm (AGRO).

	Energy (kcal)	Protein (gr)	Total fat (gr)	Carbohydrates (gr)	Calcium (mg)	Iron (mg)	Magnesium (mg)	Zinc (mg)
Average daily supply	2564	85	118	293	800	31	806	13

https://doi.org/10.1371/journal.pstr.0000066.t003

expressed as percentage of the RDA/AI of an adult male, but fat intake is referenced to 30% of the energy intake (based on the acceptable macronutrient distribution range, AMDR, which for fat is 20–35% of total energy intake). Values above and below 100% indicate nutritional adequacy or insufficiency respectively. Closely tracking vegetable seasonality, supply of all nutrients peaks in winter and attains a minimum at the end of summer. Apart from calcium, supply of all nutrients meets or exceeds the nutritional needs of an adult male, in some cases by large margins (e.g., >150% for zinc or >200% for iron). The supply of calcium ranges between 60%-130%, rendering it as the limiting nutrient in the agroecological system. Incidentally, calcium is also the limiting nutrient in the other two conventional systems, BAU and MIX (section 3.4.2.).

In terms of macronutrients distribution, the macronutrients produced on farm supply 49% carbohydrates, 37% fats, and 14% protein of total caloric output, meeting the Acceptable Macronutrients Distribution Range (AMDR; 55%-70%, 20%-35%, and 10%-35% of total calories respectively). Daily mean supplies of fatty acids are similarly desirable: 14.7 g of saturated, 13.2 g of polyunsaturated, and 71.5 g monounsaturated. Supply of the two polyunsaturated fatty acids for which AI exists—linoleic and linolenic fatty acids—were 12.1 g d^{-1} and 1.2 g d^{-1}, respectively.

3.4 Comparison of the agroecological farm to local conventional farming

3.4.1 Environmental comparison. Fig 4 presents an absolute and relative comparative LCA results per unit mass of produce (left column 4A) and per land area (right column 4B) for the three systems, AGRO, MIX and BAU. The AGRO scenario outperforms both alternative scenarios in all environmental metrics. Per unit mass (Fig 4A), the environmental burdens of

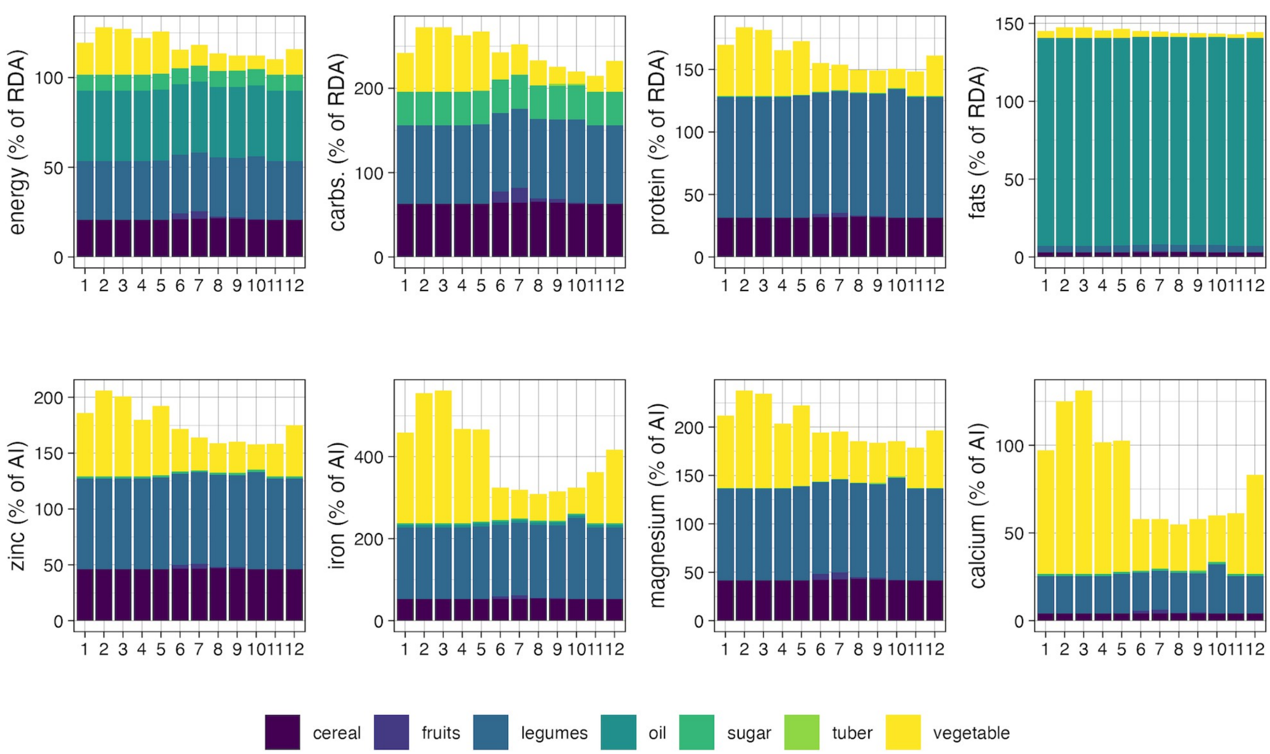

Fig 3. Nutritional supply of the total agroecological farm produce per month and per food group as percentage of the Recommended Dietary Allowance or Adequate Intake (RDA or AI) of an adult male. Values above (below) 100% indicate nutrient adequacy (deficiency).

https://doi.org/10.1371/journal.pstr.0000066.g003

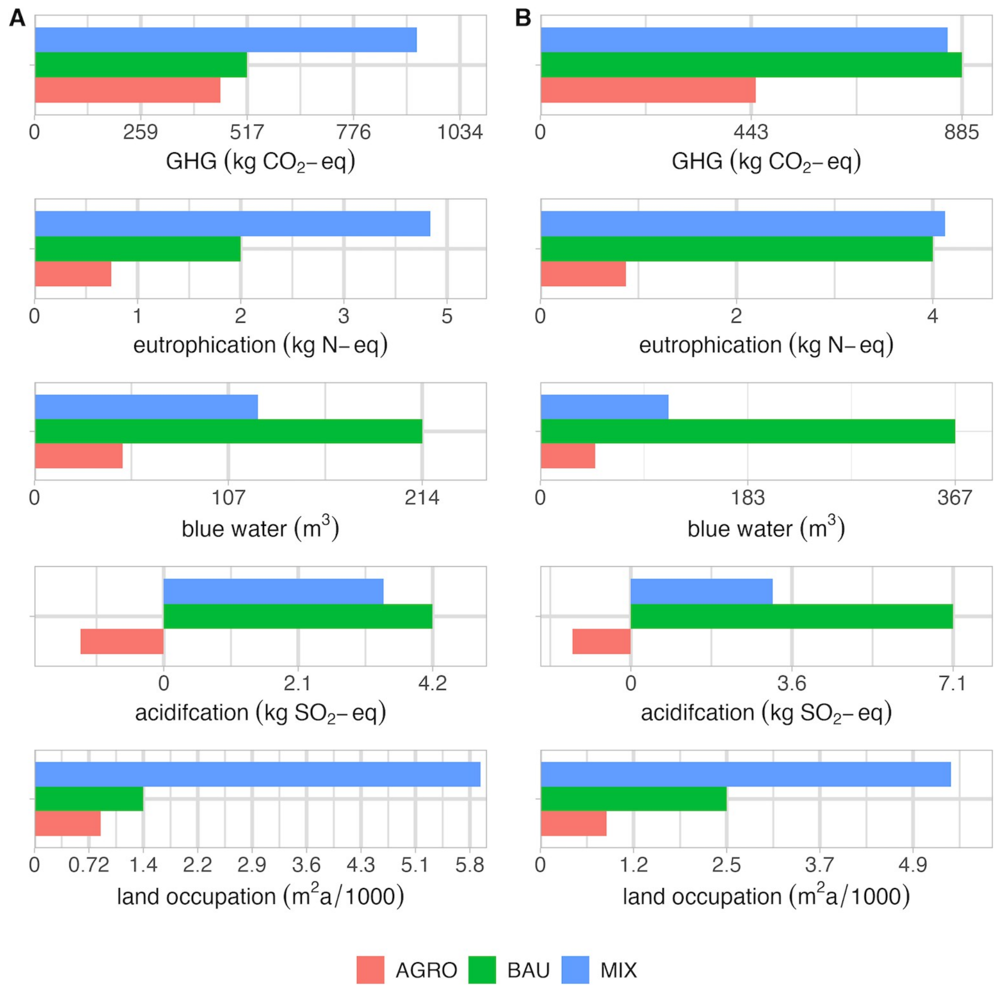

Fig 4. Absolute and relative comparative LCA per mass unit produced (column A) and per area (column B) for the three systems, AGRO, MIX and BAU. Absolute values are depicted for each subplot along with its respective units. Relative comparisons to the BAU are denoted using the gridlines, where the space between each grid line represents 25% difference from the BAU system. The BAU system is marked as 100% (fourth grid line from 0). GHG stands for greenhouse gasses.

https://doi.org/10.1371/journal.pstr.0000066.g004

the AGRO and MIX systems are between -31% to 88%, and 57% to 414% compared to BAU, respectively (with BAU fixed at 100%). Per unit agricultural land area (Fig 4B), AGRO's and MIX's resource requirements are between -18% to 51% and 31% to 221% of BAUs, respectively. A negative impact category indicates a situation when the credit that the system receives for a certain avoided burden exceeds the sum of all of the system's other contributions to the same impact (see Table F in S1 Appendix, and 'LCA' spreadsheet in S1 Data).

While in Fig 4B the three systems are compared per unit of agricultural land area (863 m^2), their land occupations (denoted 'land occupation' in Fig 4) are not identical, because this LCA category includes not only the actual agricultural area, but also supporting lands required for producing fuel, materials, compost/fertilizer, and their related infrastructure and activities. One fact that stands out in Fig 4 is the exceptionally high land occupation of MIX. By contrast to the AGRO system, where crops are grown in between and under the olive trees, conventional agriculture grows olives on separate plots, thus significantly increasing the farmland area used per tree, and hence, entails low yields per area. Since MIX, by definition, produces the same crop mix as AGRO, under conventional Israeli production methods, and since olive oil constitutes a considerable portion of AGRO's (and hence of MIX's) portfolio, the land occupation of MIX becomes exceptionally high relative to that of AGRO. Specifically, olive oil occupies 0.5 ha out of the 0.6 ha of land occupation per mass unit of 728 kg (See "LCA" spreadsheet in S1 Data).

To explore uncertainties, we calculated an alternative composting scenario (see Methods section 2.2.4). GHG emissions, marine eutrophication, biodiversity losses, and terrestrial acidification were 49%, 80%, 91% and 6% of the respective values in the current AGRO scenario (see 'LCA' spreadsheet in S1 Data). However, no changes in the ranking of AGRO/ MIX/ BAU were found.

We also tested the sensitivities of our results by exploring the differences between average global yields and Israeli yields, the latter being frequently lower. Changing the yields of MIX and BAU from Israeli yields to global ones indeed substantially reduced their impacts (often >100%, see 'LCA Figures' spreadsheet in S1 Data). Nonetheless, impacts of the AGRO scenario were still lower than those of MIX and BAU for both functional units (namely, per same output and per same area), except for a slightly (2%) lower blue water use in the MIX scenario and lower GHG (11%) in the BAU scenario per unit mass. In other words, changing the yields did not change the ranking between AGRO/ MIX/ BAU scenarios.

3.4.2 Nutritional comparison. Fig 5 depicts annual nutritional sufficiencies of the three systems (in percentages of their respective RDA/AIs, marked as 100%) of various macro- and micro-nutrients per identical mass produced and per identical agricultural area. For a list of average daily nutrient supply for the three systems in absolute numbers—per unit mass and

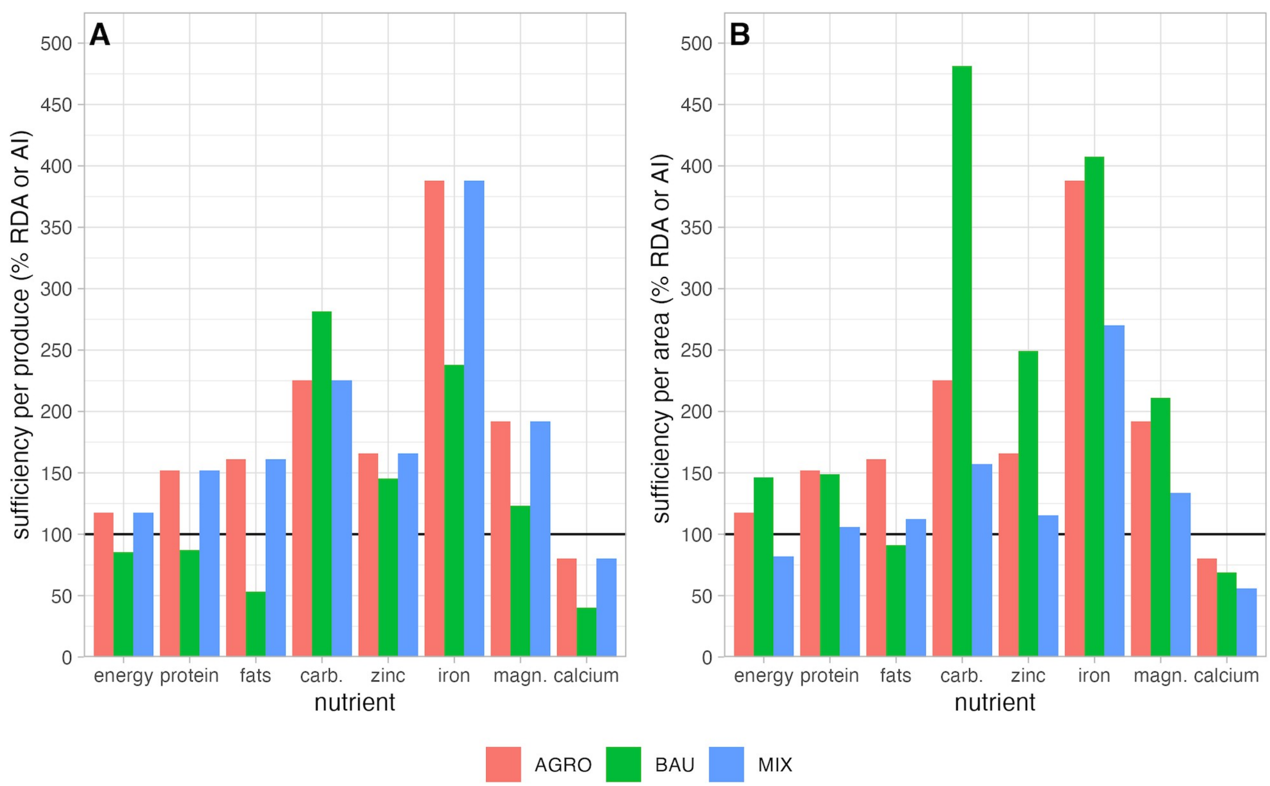

Fig 5. Nutritional sufficiency of the diets delivered by the three considered systems, AGRO, BAU, and MIX, calculated per unit mass (A) or land (B). Nutritional supply values are expressed as percentages of recommended adult male intake. Values above (below) 100% indicate nutritional sufficiency (inadequacy) of an adult male. Energy stands for calories; carb. for carbohydrates; and magn. for magnesium.

https://doi.org/10.1371/journal.pstr.0000066.g005

per unit area—see Table B in S1 Appendix. (For more details, See 'comparative analysis' spreadsheet in S1 Data).

The 728 kg from the agroecological farm (AGRO) delivers more of all nutrients save carbohydrates than the 728 kg produced by the mean Israeli conventional farming (BAU; Fig 5A), indicating that the agroecological crop mix has on average more nutritional content per kg than its conventional counterpart (BAU). Since by construction, AGRO and MIX outputs are the same in mass and composition, their nutritional contents are identical (Fig 5A).

Conversely, per unit agricultural area (Fig 5B), conventional farming (BAU) outperforms the AGRO in five out of eight nutrients. Put differently, although the AGRO farm produces foods with more nutritional content per unit mass relative to conventional farming, it has a slightly lower average nutritional yield (i.e., less nutritional content per m^2). Because nutrient yields are a multiplication of total mass yields and nutritional content per unit mass, this can only mean that the average total yield (i.e., mass per area) of BAU is greater than that of AGRO. This is also directly confirmed by the data (see 'per farm's area' spreadsheet' in S1 Data). However, these larger yields are achieved via larger inputs and result in higher environmental impacts (see Section 3.4.1).

Across all nutrients examined, the AGRO system produces higher nutritional yields than the MIX system per equal land area (Fig 5B), although producing the same crop mixtures. Specifically, despite using conventional practices, the MIX system requires 44% more farmland relative to the AGRO farm (see 'per output' spreadsheet in S1 Data). This is mainly due to the spatial overlap (intercropping) used on the agroecological farm to cultivate wheat, pulses and vegetables together with the olive trees, so that the former three are cultivated up to the trunks of the trees. Conversely, conventional farming grows each of these crops on separate plots of land (monoculture), and hence, producing the same amount of wheat, pulses, vegetables and oil requires considerably more farmland. It thus follows that for a fixed farmland area, the MIX farmland will produce less harvest (in mass) relative to AGRO and hence less nutrients, as indicated in Fig 5B (see "Comparative Analysis" spreadsheet in S1 Data for further details).

When considering the LCA category of land occupation—i.e., all land area required for the production of crops (farmland, and supporting land for producing fuel, materials, compost/fertilizer etc.)—the area occupied by MIX and BAU increases by 6.3 and 2.9 times, respectively (relative to their farmland use), whereas that of AGRO increases by a negligible 2%. In other words, when considering land occupation, the nutritional yields (nutrition per area) of MIX and of BAU drop by 6.3 and 2.9 folds respectively, whereas AGRO's nutritional yield remains virtually unchanged. Consequently, by using land occupation rather than agricultural land, the nutritional yields of AGRO is 2.7 and 8.7 folds higher than that of the BAU and MIX systems, respectively (See 'Comparative Analysis' spreadsheet in S1 Data).

3.4.3 Combined environmental and nutritional analysis. We combined the nutritional and environmental analyses of the three systems to facilitate a comparison across a nutritional-environmental space. The comparison is conducted per mass (Fig 6A) and per similar farmland area (Fig 6B), in percentages relative to BAU, which is situated at the intersection of 100%. We calculated a nutritional quality score for each of the systems by averaging their nutrients supply in comparison to BAU, to derive a relative nutritional score. Thus, for example, the relative nutritional score of AGRO per mass-produce is 166% relative to BAU (indicated by the red icons in Fig 6A), whereas the relative nutritional score of AGRO per area is 97% relative to BAU (indicated by the red icons in Fig 6B). We used both relative individual environmental impact categories as well as a composite environmental indicator termed 'Total', which is the average relative difference of all the environmental impacts compared to BAU. For example, AGRO produces only 51% GHG emissions relative to BAU per the same area (red triangle in Fig 6B), whereas AGRO produces 89% GHG emissions relative to BAU

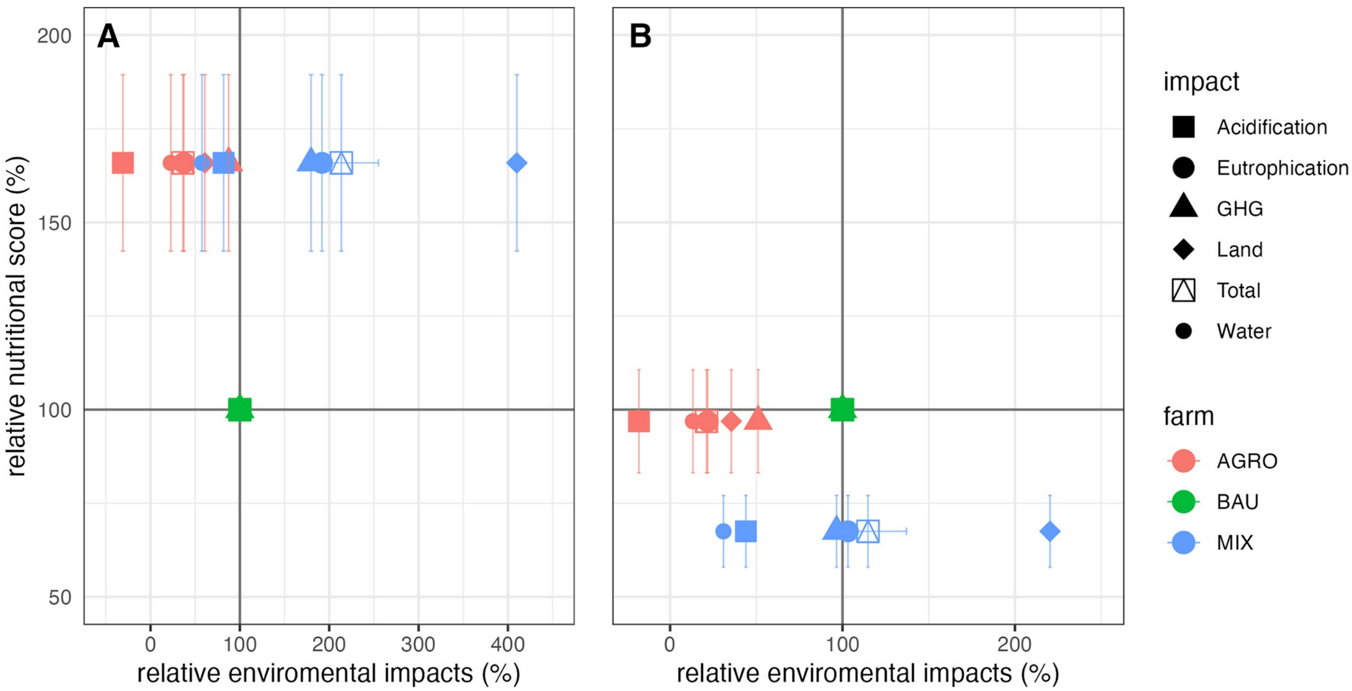

Fig 6. Relative nutritional and environmental scores for two systems (AGRO and MIX) per mass produced (A) and fixed land area (B) in percentages differences from BAU, which is denoted as 100% for all environmental and nutritional metrics. Nutritional quality (y axis) is presented using a relative nutritional score compared to BAU, calculated as the average relative nutritional scores of all eight nutritional values. 'Total' stands for a relative environmental indicator calculated as the average relative environmental scores of all environmental impacts (including others not included in this figure) (See 'comparative analysis' spreadsheet in S1 Data). Y error bars mark the spread (standard error) of individual relative nutritional scores (e.g. of energy, protein etc); X error bars highlight the spread (standard error) of individual relative environmental scores within the composite environmental indicator ('Total'). GHG stands for greenhouse gas emissions; Water—for blue water usage; Land—for land occupation; and Biodiversity—for biodiversity loss.

https://doi.org/10.1371/journal.pstr.0000066.g006

per the same mass produce (red triangle in Fig 6A). (See 'comparative analysis' spreadsheet in S1 Data for details.) The composite environmental score of AGRO per mass-produce relative to BAU is 36% (indicated by the red 'Total' icon in Fig 6A), whereas the composite environmental score of AGRO per area relative to BAU is 21% (indicated by the same red icon in Fig 6B).

The MIX system always resides to the right and below of AGRO, indicating environmental and nutritional inferiority compared to AGRO. The AGRO system is nutritionally and environmentally better than BAU on an equal mass basis (indicated by the fact that the green icons are always to the right and below the red ones in Fig 6A). The BAU system's relative nutritional score for a fixed land area (Fig 6B) is slightly higher than AGRO's (green icons are slightly above the red ones), but with significantly higher environmental impacts (green icons are to the right of the red ones). In short, for the same agricultural land area, the AGRO system generates a mere fraction of the environmental impacts relative to the conventional farming system (BAU) (on average 21%), while supplying nearly the same nutritional quality (97%) (see 'Comparative Analysis' spreadsheet in S1 Data). When considering land occupation (and not only agricultural land) the nutritional-environmental superiority of the AGRO system stands out.

4. Discussion

4.1 Synthesis

We studied a self-sufficient small-scale agroecological farm and compared it to local conventional farming by documenting all its inputs and outputs. This comparison included yield and nutritional supply, and we used LCA to compare environmental impacts such as GHG, acidification, eutrophication, land use, and water use. Our results show that the agroecological farm outperformed local conventional agriculture in all environmental indicators and in most nutritional indicators. Even in terms of nutritional yield per agricultural area, where conventional agriculture performed better, the difference between these two agricultural practices is negligible. Our study thus provides further support for the benefits of agroecological farming as indicated in other studies [43–45] and highlights the importance of a nutrition-sensitive approach to its implementation [28].

From a nutritional standpoint, the agroecological farm provided sufficient nutrients to meet the needs of a single person, with the exception of calcium. However, calcium retention in the body depends on other factors apart from intake, including the Calcium/Phosphorus ratio and protein intake. Some studies suggest that a diet rich in fruits, vegetables, and plant-based proteins decreases urinary calcium loss [46,47]. In addition, the mean calcium production of the farm was 826±280 mg/d, which is above the lower limit that may increase the risk for fractures [48]. In terms of fat intake, the types of fatty acids produced and their ratios are important to establish health outcomes, not only total fat intake. Several approaches have been proposed in this context for such recommended ratios, such as (polyunsaturated+ monounsaturated)/saturated fatty acids, monounsaturated/saturated fatty acids, polyunsaturated/monounsaturated, or the percent of the different fatty acids types from total caloric consumption [49–51]. Given that the farmer consumes only half of the olive oil—which is the major source of monounsaturated fatty acids, dietary consumption of essential fatty acids is slightly lower than recommended AI for polyunsaturated linoleic and linolenic fatty acids. However, the fatty acid mixtures consumed support health and meet nutritional recommendations for fat consumption [50,51].

Industrial farming was initially designed to produce high yields through water and synthetic fertilizer inputs but has considerable environmental consequences, as is evident by the fragmentation of pristine habitats, large land and water resource usage and the resulting air, land and water pollution [52]. Consequently, it is usually perceived that there is a trade-off between increasing yield and environmental impacts, and that nature-based agroecological food systems with very low inputs compromise yields and therefore food security [53]. Using nutritional and environmental analysis of agroecology in comparison to local conventional farming, we provide further evidence that challenges this line of thought [43]. In comparison to local average conventional agriculture, we find that the agroecological farm produces a crop basket with more nutrients per unit mass, with considerably lower environmental impacts due to a better crop portfolio. Per unit of arable land, the average nutritional yield of the agroecological farm is nearly the same as that of conventional agriculture (97%), but on average environmental costs are 79% lower. Taking note of total land occupation (arable plus non-agricultural supporting lands), the nutritional and environmental performance of the agroecological farm is far greater. Furthermore, the system boundaries of this study are "cradle to farmgate" (see Fig 1), and therefore the study ignores supply chain losses (e.g., food waste), which is estimated at approximately 40% of production [54]. Incorporating actual consumed nutritional supply estimates would have doubled the nutritional supply of the agroecological farm compared to the conventional food system, because food waste on the farm is nearly zero, thereby further increasing its advantage over conventional systems to supply nutrition to humans.

4.2 Implications

The farm studied here includes salient and unique features that provide valuable lessons for designing sustainable food systems. First, the harvest produced on the farm was designed to be nutrition-sensitive to meet dietary requirements, such that nutrition was assessed not only as an outcome but also as a determinant for agricultural production and practices [28]. Consequently, the farm produces a high proportion of vegetables that many diets globally lack and are in short supply to curb adverse health outcomes including micronutrient deficiencies [54]. Globally, agriculture production is often commodity-driven and therefore focuses on cereals and sugars, which together constitute more than half of production [55], rather than on positive nutritional outcomes [56]. In this respect, the farm's planning and design provides an important benchmark to the types and proportions of crops needed to divert agriculture to be more nutritionally-sensitive. Specifically, this includes not only concentrating the bulk of production on vegetables, but also incorporating other important crops for human and soil health, such as legumes, which, in addition to being a protein-source, also serve as nitrogen fixers, naturally fertilizing the soil. Second, the farm was also designed to minimize environmental impacts and resource usage, and to enhance resilience. In addition to producing no waste, the farm involves no packaging and transport, further highlighting the benefits of small-scale and localized food systems and their ability to cope with external shocks [57]. Third, an important feature of the farm is the cultivation of about 40 crops on a small area, whereas the respective conventional agricultural system (BAU) cultivates about 60 crops in monocultures on 0.3 Mha in Israel. Agrobiodiversity at the field-scale, which is not considered in our analysis, is important in providing increased productivity [58] at greater stability [59] and facilitating interactions towards positive agricultural outcomes. The cultivation of multiple crops—each with unique features and requirements—can also provide opportunities for better resource management and outcomes. For example, growing wheat and fava interspersed between olive trees is a valuable strategy to save land resources.

In addition, moving from the field level to the landscape level, such diverse landscapes—as opposed to monocultures—are tied to cultural heritages [60] and provide multiple ecosystem services if designed properly [61]. Further studies at the field and landscape level should reveal how the types of crops and their spatial arrangement foster positive synergistic interactions and identify the optimal region-specfic crop assemblages and agroecological practices that reap maximum benefits across nutritional, environmental and societal dimensions.

Although our analysis is based on a single agroecological farm in a single country, it contributes to the agroecology literature in various ways. First, studies in agroecology and food production in Mediterranean regions are scarce. Second, nutritional analysis of agroecological production is lacking and more studies incorporating nutrition and human health dimensions should be promoted. Third, to our knowledge, this is the first LCA that compares a polyculture farm to a conventional farming system. Our nutritional-environmental analysis invites more similar comparisons of agroecology to conventional farming in other regions of the world. Last, the highly advanced agriculture in Israel makes the achievement of agroecology outperforming Israel's conventional yields all the more striking.

4.3 Limitations

A limitation of our analysis is that because it addresses a single system, and thus provides preliminary rather than firm conclusions, our findings cannot be thought of as representative of agroecological systems writ large. This limitation is, for now, insurmountable; there just aren't enough studied systems to be pooled with our analysis into statistical conclusions. Our results are therefore not a maximum likelihood estimate of the potential of widely deployed agroecological enterprises. Rather, they illuminate what is possible. At the very least they are a best-case scenario but more likely as a good but not best-case (because there is little reason to assume the single studied system is the best).

Our analysis does not take note of other important considerations, such as labor and economic viability, which future studies should explore. Upscaling the agroecological farm will likely require more manual labor, but would provide opportunities to develop new machinery that will enable cultivating (mainly sowing and harvesting) complex arrangements of trees and cereal/legumes on a larger scale without compromising field-level agrobiodiversity. With a large turnover, a focus on vegetables can also provide large income returns [28]. When internalizing the large health and environmental impacts of conventional agriculture, the economic impetus for governments to support such transitions in agricultural systems via supporting policies and investments becomes apparent.

5. Conclusions

The need to radically rethink food systems worldwide, and rectify their many fundamental problems is by now virtually universally agreed upon. Yet the alternatives advocated vary so widely as to often mutually contradict one another. Some of this divergence highlights different foundational axioms various analyses are premised on, and a remainder is attributable to emphasizing one or another environmental or nutritional objective. But much of it makes clear that no silver bullet will do, and that multiple approaches will be required to thoughtfully balance all environmental and nutritional objectives in a nuanced manner that takes note of the vast plethora of geographical, cultural, and culinary customs the global food system unifies. In this spirit, this paper analyzes a novel approach that combines an environmental and nutritional analyses simultaneously, to showcase the potential of nutritionally-sensitive agroecological methods. Moving forward, further studies will need to examine other important aspects not addressed here, such as economic viability, which will be crucial in order to determine what elements of this unique farm, and to what extent, ought to be upscaled. Nevertheless, our study already provides the cornerstone for alternative agricultural practices that may well be key additional tools in the wide-ranging toolkit we need to substantially better our food systems.

Supporting information

S1 Appendix. Supplementary sections, figures and tables.
(PDF)

S1 Data. Dataset.
(XLSX)

Acknowledgments

The authors wish to thank Prof. Ohad Nachtomy for suggesting to conduct this research project.

Author Contributions

Conceptualization: Alik Pelman, Alon Shepon.

Data curation: Alik Pelman, Alon Shepon.

Formal analysis: Alik Pelman, Jerke W. De Vries, Sigal Tepper, Alon Shepon.

Investigation: Alik Pelman.

Methodology: Alik Pelman, Jerke W. De Vries, Sigal Tepper, Alon Shepon.

Project administration: Alik Pelman, Alon Shepon.

Supervision: Alik Pelman, Alon Shepon.

Validation: Alik Pelman, Jerke W. De Vries, Sigal Tepper, Gidon Eshel, Yohay Carmel, Alon Shepon.

Visualization: Jerke W. De Vries, Alon Shepon.

Writing – original draft: Alik Pelman, Jerke W. De Vries, Sigal Tepper, Alon Shepon.

Writing – review & editing: Alik Pelman, Jerke W. De Vries, Sigal Tepper, Gidon Eshel, Yohay Carmel, Alon Shepon.

References

1. Clark MA, Domingo NGG, Colgan K, Thakrar SK, Tilman D, Lynch J, et al. Global food system emissions could preclude achieving the 1.5˚ and 2˚C climate change targets. Science. 2020; 370: 705–708.
2. Zimmerer KS, de Haan S, Jones AD, Creed-Kanashiro H, Tello M, Carrasco M, et al. The biodiversity of food and agriculture (Agrobiodiversity) in the anthropocene: Research advances and conceptual framework. Anthropocene. 2019; 25: 100192.
3. Zaccari C, De Vivo R, Pawera L, Termote C, Hunter D, Borelli T, et al. Lessons learned from the Second International Agrobiodiversity Congress: Adopting agricultural biodiversity as a catalyst for transformative global food systems. Current Opinion in Environmental Science & Health. 2023; 31: 100411.
4. Messer KD, Costanigro M, Kaiser HM. Labeling food processes: The good, the bad and the ugly. Appl Econ Perspect Policy. 2017; 39: 407–427.
5. Levkoe C, Wakefield S. The Community Food Centre: Creating Space for a Just, Sustainable, and Healthy Food System. J Agric Food Syst Community Dev. 2011; 2: 249–268.
6. Faccioli M, Law C, Caine CA, Berger N, Yan X, Weninger F, et al. Combined carbon and health taxes outperform single-purpose information or fiscal measures in designing sustainable food policies. Nature Food. 2022; 3: 331–340. https://doi.org/10.1038/s43016-022-00482-2 PMID: 37117577
7. Clapp J. The problem with growing corporate concentration and power in the global food system. Nature Food. 2021. pp. 404–408. https://doi.org/10.1038/s43016-021-00297-7 PMID: 37118223
8. Patel R. Food sovereignty. J Peasant Stud. 2009; 36: 663–706.
9. Tomich TP, Brodt S, Ferris H, Galt R, Horwath WR, Kebreab E, et al. Agroecology: A Review from a Global-Change Perspective. Annual Review of Environment and Resources. 2011. pp. 193–222. https://doi.org/10.1146/annurev-environ-012110-121302
10. Wezel A, Soldat V. A quantitative and qualitative historical analysis of the scientific discipline of agroecology. Int J Agric Sustainability. 2009; 7: 3–18.
11. Pörtner HO, Roberts DC, Adams H, Adler C, Aldunce P, Ali E, et al. Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva : Intergovernmental Panel on Climate Change (IPCC). 2022. 36 p.
12. IPBES. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio E, Settele J, Díaz S, Ngo HT, editors. Bonn, Germany; 2019. p. 1444.
13. HLPE. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. 2019. HLPE report #14.
14. Boeraeve F, Dendoncker N, Cornélis J-T, Degrune F, Dufrêne M. Contribution of agroecological farming systems to the delivery of ecosystem services. Journal of Environmental Management. 2020. p. 109576. https://doi.org/10.1016/j.jenvman.2019.109576 PMID: 32046879
15. Timmermann C, Félix GF. Agroecology as a vehicle for contributive justice. Agric Human Values. 2015; 32: 523–538.
16. Zaremba H, Elias M, Rietveld A, Bergamini N. Toward a Feminist Agroecology. Sustain Sci Pract Policy. 2021; 13: 11244.
17. Chavez-Miguel G, Bonatti M, Ácevedo-Osorio Á, Sieber S, Löhr K. Agroecology as a grassroots approach for environmental peacebuilding: Strengthening social cohesion and resilience in post-conflict settings with community-based natural resource management. GAIA—Ecological Perspectives for Science and Society. 2022. pp. 36–45. https://doi.org/10.14512/gaia.31.1.9

18. Anderson CR, Bruil J, Chappell MJ, Kiss C, Pimbert MP. From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. Sustain Sci Pract Policy. 2019; 11: 5272.

19. Gliessman S. Transforming food systems with agroecology. Agroecology and Sustainable Food Systems. 2016; 40: 187–189.

20. ISO. Environmental management—Life cycle assessment—Principles and framework. 2006. Report No.: 14040:2006. Available: https://www.iso.org/standard/37456.html

21. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. Science. 2018; 360: 987–992. https://doi.org/10.1126/science.aaq0216 PMID: 29853680

22. Clark M, Tilman D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett. 2017.

23. Bezner Kerr R, Madsen S, Stüber M, Liebert J, Enloe S, Borghino N, et al. Can agroecology improve food security and nutrition? A review. Global Food Security. 2021; 29: 100540.

24. Li C, Stomph T-J, Makowski D, Li H, Zhang C, Zhang F, et al. The productive performance of intercropping. Proc Natl Acad Sci U S A. 2023; 120: e2201886120. https://doi.org/10.1073/pnas.2201886120 PMID: 36595678

25. Gascuel-Odoux C, Lescourret F, Dedieu B, Detang-Dessendre C, Faverdin P, Hazard L, et al. A research agenda for scaling up agroecology in European countries. Agron Sustain Dev. 2022; 42: 53. https://doi.org/10.1007/s13593-022-00786-4 PMID: 35702339

26. van der Werf HMG, Knudsen MT, Cederberg C. Towards better representation of organic agriculture in life cycle assessment. Nature Sustainability. 2020; 3: 419–425.

27. Deaconu A, Berti PR, Cole DC, Mercille G, Batal M. Agroecology and nutritional health: A comparison of agroecological farmers and their neighbors in the Ecuadorian highlands. Food Policy. 2021; 101: 102034.

28. van Zutphen KG, van den Berg S, Gavin-Smith B, Imbo E, Kraemer K, Monroy-Gomez J, et al. Nutrition as a driver and outcome of agroecology. Nature Food. 2022; 3: 990–996. https://doi.org/10.1038/s43016-022-00631-7 PMID: 37118296

29. Toperoff G, Greenhot Z, Levengrat A. Sustainable nutrition and national food security in Israeli agriculture—quantitative values from crops. In hebrew. Ecology and Environment, Israel Society of Ecology and Environmental Sciences. 2018; 9: 18–27.

30. Israeli Plants Production and Marketing Board. Plant production and yields in Israel (in Hebrew). In: http://www.plants.org.il/ [Internet]. 2018 [cited 2022]. Available: http://www.plants.org.il/uploadImages/systemFiles/AVGYulandFb11-2018.pdf

31. Israeli ministry of Health. Tzameret nutritional database. In: Tzameret nutritional database [Internet]. 2022 [cited 2022]. Available: https://www.health.gov.il/Subjects/FoodAndNutrition/Nutrition/professionals/Pages/Tzameret.aspx

32. IOM. DRI Dietary Reference Intakes: Applications in Dietary Assessment. The National Academies Press, editor. Washington (DC): National Academies Press (US); 2000.

33. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 2009; 1: 1–126.

34. Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, et al. USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess. 2008; 13: 532–546.

35. Ecoinvent. EcoinventCentre. Final Reports 2020. 2020. Ecoinvent Data v3.0.

36. Ba S, Qu Q, Zhang K, Groot JCJ. Meta-analysis of greenhouse gas and ammonia emissions from dairy manure composting. Biosystems Eng. 2020; 193: 126–137.

37. Brinkmann AJF, Van Zundert EHM, Saft RJ. Herziening levenscyclusanalyse voor GFT-afval. Herberekening LCA bij het MER-LAP. 2004.

38. NutriNorm. De samenstelling van organische meststoffen. 2016. Available: https://nutrinorm.nl/meststoffen/de-samenstelling-van-organische-meststoffen/#:~:text=Organische%20meststoffen%20bevatten%20een%20breed,ook%20binnen%20een%20bepaalde%20mestsoort.

39. De Vries JW, Vinken TMWJ, Hamelin L, De Boer IJM. Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy—a life cycle perspective. Bioresour Technol. 2012; 125: 239–248. https://doi.org/10.1016/j.biortech.2012.08.124 PMID: 23026340

40. Tiefenbacher A, Sandén T, Haslmayr H-P, Miloczki J, Wenzel W, Spiegel H. Optimizing Carbon Sequestration in Croplands: A Synthesis. Agronomy. 2021;11. https://doi.org/10.3390/agronomy11050882

41. Sharma G, Campbell A. Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems. NSW Department of Environment and Conservation, University of New South Wales/Recycled Organics Unit; 2007.
42. Abdalla M, Osborne B, Lanigan G, Forristal D, Williams M, Smith P, et al. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manage. 2013; 29: 199–209.
43. Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MGA, Liebman M, et al. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv. 2020;6. https://doi.org/10.1126/sciadv.aba1715 PMID: 33148637
44. Kremen C, Miles A. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol Soc. 2012;17. Available: https://www.jstor.org/stable/26269237
45. Chaplin-Kramer R, Chappell MJ, Bennett EM. Un-yielding: Evidence for the agriculture transformation we need. Ann N Y Acad Sci. 2022. https://doi.org/10.1111/nyas.14950 PMID: 36576483
46. Craig WJ. Health effects of vegan diets. Am J Clin Nutr. 2009; 89: 1627S–1633S. https://doi.org/10.3945/ajcn.2009.26736N PMID: 19279075
47. Deriemaeker P, Aerenhouts D, Hebbelinck M, Clarys P. Nutrient based estimation of acid-base balance in vegetarians and non-vegetarians. Plant Foods Hum Nutr. 2010; 65: 77–82. https://doi.org/10.1007/s11130-009-0149-5 PMID: 20054653
48. Appleby P, Roddam A, Allen N, Key T. Comparative fracture risk in vegetarians and nonvegetarians in EPIC-Oxford. Eur J Clin Nutr. 2007; 61: 1400–1406. https://doi.org/10.1038/sj.ejcn.1602659 PMID: 17299475
49. Kelly OJ, Gilman JC, Ilich JZ. Utilizing Dietary Nutrient Ratios in Nutritional Research: Expanding the Concept of Nutrient Ratios to Macronutrients. Nutrients. 2019;11. https://doi.org/10.3390/nu11020282 PMID: 30696021
50. Kris-Etherton PM. Monounsaturated Fatty Acids and Risk of Cardiovascular Disease. Circulation. 1999; 100: 1253–1258.
51. Commission European. Dietary recommendations for fat intake. In: Dietary recommendations for fat intake as described by food- and health-related organisations [Internet]. 2023 [cited 2023]. Available: https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/dietary-fats-table-4_en
52. Pretty J. Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond B Biol Sci. 2008; 363: 447–465. https://doi.org/10.1098/rstb.2007.2163 PMID: 17652074
53. Bateman I, Balmford A. Current conservation policies risk accelerating biodiversity loss. Nature. 2023; 618: 671–674. https://doi.org/10.1038/d41586-023-01979-x PMID: 37344644
54. Development initiatives. 2021 Global Nutrition report: The state of global nutrition. Development initiatives; 2021.
55. FAO. World Food and Agriculture–Statistical Yearbook 2021. Food & Agriculture Org.; 2021.
56. Ruel MT, Quisumbing AR, Balagamwala M. Nutrition-sensitive agriculture: What have we learned and where do we go from here? Intl Food Policy Res Inst; 2017.
57. Béné C. Resilience of local food systems and links to food security—A review of some important concepts in the context of COVID-19 and other shocks. Food Secur. 2020; 12: 805–822. https://doi.org/10.1007/s12571-020-01076-1 PMID: 32837646
58. Duffy JE, Godwin CM, Cardinale BJ. Biodiversity effects in the wild are common and as strong as key drivers of productivity. Nature. 2017; 549: 261–264. https://doi.org/10.1038/nature23886 PMID: 28869964
59. Renard D, Tilman D. National food production stabilized by crop diversity. Nature. 2019; 571: 257–260. https://doi.org/10.1038/s41586-019-1316-y PMID: 31217589
60. Barbera G, Cullotta S. The Traditional Mediterranean Polycultural Landscape as Cultural Heritage: Its Origin and Historical Importance, Its Agro-Silvo-Pastoral Complexity and the Necessity for Its Identification and Inventory. In: Agnoletti M, Emanueli F, editors. Biocultural Diversity in Europe. Cham: Springer International Publishing; 2016. pp. 21–48.
61. Jeanneret P, Aviron S, Alignier A, Lavigne C, Helfenstein J, Herzog F, et al. Agroecology landscapes. Landsc Ecol. 2021; 36: 2235–2257. https://doi.org/10.1007/s10980-021-01248-0 PMID: 34219965