Org. Agr.
https://doi.org/10.1007/s13165-022-00394-2

# A review of scientific research on biodynamic agriculture

**Margherita Santoni · Lorenzo Ferretti · Paola Migliorini · Concetta Vazzana · Gaio Cesare Pacini**

Received: 24 April 2021 / Accepted: 18 May 2022


**Abstract** Biodynamic agriculture (BD agriculture) was presented as an alternative form of agriculture by the philosopher Rudolf Steiner and is nowadays considered one of the forms of organic agriculture. The objective of the present manuscript is to critically review international scientific literature on biodynamic agriculture as published in highly ranked journals and to assess its performance. This review was based on a structured literature survey of peer-reviewed journals indexed on the Web of Science™ (WoS) Core Collection database carried out from 1985 until 2018. We found 147 publications of studies in journals with an impact factor. Of these, 93 focused on biodynamic agricultural practices, 26 on the sustainability of the biodynamic method, and 28 on the food quality of biodynamic products. The results of the literature review showed that the BD method enhances soil quality and biodiversity. Instead, further efforts are needed to implement knowledge on the socio-economic sustainability and food quality aspects of BD products. One particularly promising topic of research consists in the assessment of microbial activity and the potential that microbiomes have in BD farms to enhance soil fertility and human health following the One Health approach. Moreover, it is critical that such subjects be investigated using a systemic approach. We conclude that BD agriculture could provide benefits for the environment and that further efforts should be made with research and innovation activities to provide additional information to farmers, policy makers, and stakeholders regarding this type of organic agriculture.

**Keywords** Literature review · Biodynamic agriculture · Organic agriculture · Agricultural practices · Sustainability · Food quality

## Introduction

Biodynamic agriculture (BD agriculture) was presented as an alternative form of agriculture by the philosopher Rudolf Steiner (Steiner 1924) and is nowadays considered one of the forms of organic agriculture. The BD method is based on a closed production system that aims to reproduce an agro-ecological model focused on a reduction of energy

M. Santoni (✉) · L. Ferretti · C. Vazzana · G. C. Pacini
Department of Agricultural, Food, Environmental and Forestry Sciences (DAGRI), University of Florence, Florence, Italy
e-mail: margherita.santoni@unifi.it

L. Ferretti
e-mail: lorenzo.ferretti@unifi.it

C. Vazzana
e-mail: concetta.vazzana@unifi.it

G. C. Pacini
e-mail: gaiocesare.pacini@unifi.it

P. Migliorini
University of Gastronomic Sciences of Pollenzo, Bra, Italy
e-mail: p.migliorini@unisg.it

Published online: 07 June 2022

consumption and capable of achieving high levels of environmental efficiency. The method has been institutionalized by the international certification label Demeter® (Döring et al. 2015). As reported by Willer et al. (2020), since the turn of the millennium, Demeter-certified farms have grown significantly in number (more than 5900 farms in June 2019), and the certified surface area has almost doubled to over 200,000 ha in 63 countries. Germany has the largest BD area (34% of the world total), followed by Australia (20%), and France (6%) (Paull et al. 2020). In total, around 15,000 ha of the Demeter-certified area are biodynamic vineyards, with around 760 BD wineries in Europe, led by France with 375 wineries (Willer et al. 2020). In comparison to the global total of 71.5 million certified organic hectares, BD farming represents a small niche as it covers only 0.35% of the land in question (Paull and Hennig 2020).

BD and organic agriculture share most principles and rules; however, Demeter's production rules include restrictions on many organic farming practices in order to strengthen the multifunctional role of the farm. Demeter-certified farms fully comply with organic agriculture rules but impose additional obligations. The main differences between Demeter and organic production rules as defined by the International Federation of Organic Agriculture Movements (IFOAM) concern the use of specific preparations applied to crops or soil in very small amounts (Table 1), the obligation to leave 10% of the total farm area available for ecological infrastructures, and the obligation to rear animals on the farm (0.2 livestock units per hectare). While the use of preparations has always been compulsory, the minimum ecological infrastructure areas rule entered into force recently, and the constraint on animals currently applies only to Italian farms (Demeter Associazione Italia). However, although in the past, only preparations were normed, it has always been standard practice for BD farms to promote biodiversity and rear animals within the farm.

The hypothesis at issue is whether BD methods possess the capacity to support optimum performances in terms of agroecosystems and human health. In recent decades, international research has examined BD agriculture to assess whether the BD method affects ecosystems, crops, and products. Even though the BD method is not in widespread use around the world, these aspects, combined with potential impacts on biodiversity and overall sustainability, make the BD method an interesting option for agroecosystem management. The number of scientific studies investigating BD agriculture is restricted when compared to those investigating organic agriculture, which has attracted considerable interest in the scientific community. The first studies specifically focusing on the BD method were carried out between the end of the 1980s and the beginning of the 1990s, while the most recent peer-reviewed research into BD agriculture was published by Turinek et al. in 2009. On the basis of these considerations, the objective of this paper is to critically review international scientific literature on BD agriculture as published in highly ranked journals and to assess its performance, as well as to detect any lack of knowledge on relevant issues in agriculture, if any exist. In the concluding section, the results obtained are discussed in the context of the development of sustainable agriculture, with some specific suggestions for further development of BD research.

**Table 1** List of the main biodynamic preparations (Masson 2009)

| Number of preparations | Main ingredient |
|---|---|
| 500 | Cow manure |
| 500P | Preparation 500 with 502–507 |
| 501 | Silica |
| 502 | Yarrow flowers (*Achillea millefolium*) |
| 503 | Camomile flowers (*Matricaria recutia*) |
| 504 | Stinging nettle shoots (*Urtica dioica*) |
| 505 | Oak bark (*Quercus robur*) |
| 506 | Dandelion flowers (*Taraxacum officinale*) |
| 507 | Valerian extract (*Valeriana officinalis*) |
| Compost | Cow manure with preparation 502 to 507 |

## Materials and method

A review of international scientific literature on BD agriculture was conducted with specific reference to highly ranked journals. The review was based on a structured literature survey of peer-reviewed journals indexed on the Web of Science™ (WoS)

Core Collection database carried out for all years from 1985 until 2018. All possible combinations of the terms "biodynamic," "bio-dynamic," "agriculture," and "farming" were used for the literature search and no other search terms were considered as we wanted to focus exclusively on studies aimed specifically at BD agriculture. Conference proceedings were excluded from the search. The whole set of WoS categories were considered. The document types considered were articles and reviews published in English in scientific journals with impact factor. The references were exported to our database; double entries and material not related to BD agriculture were excluded.

Statistical analyses were conducted on accumulation of BD agriculture publication over time and on geographical distribution utilizing R statistical software version 4.0.3 (R Core Team 2020) and one of its libraries (Wickham 2011). Articles were then grouped based on their correspondence to three topics: (a) biodynamic agricultural practices, (b) sustainability of the biodynamic method, and (c) food quality of biodynamic products. The relevance of targeted journals of BD agriculture studies was considered in terms of impact factor (IF) by dividing the publications into three categories: publications in journals with (i) $0 < \mathrm{IF} < 1$, (ii) $1 < \mathrm{IF} < 2$, and (iii) $\mathrm{IF} > 2$. For each journal, the Five-Year Journal Impact Factor™ referring to 2018 (source: Journal Citation Report™) was considered and was taken directly from the Journal information section of Web of Science™.

Additionally, we selected first-quartile articles from among those belonging to the third IF category ($\mathrm{IF} > 2$). Our qualitative remarks referred to the last category.

To compare the extent of studies carried out of BD agriculture with those conducted on Organic and Integrated Agriculture, we used more selective entries and counted total publications of literature searches for three groups of topics:

i. "Biodynamic Agriculture," "Biodynamic Farming," "Bio-dynamic Agriculture," "Bio-dynamic Farming;"
ii. "Organic Agriculture," "Organic Farming and
iii. "Integrated Agriculture," "Integrated Farming," "Integrated Crop Management," "Integrated Pest Management".

## Results

The number of articles on BD agriculture published between 1985 and 2017 is shown in Fig. 1. Publication of research in journals with impact factor started recently, i.e., 1990, for a total amount of 147 articles, of which 87 were published in the last decade. This means that in 33 years of potential publication, less than five articles per year have been published. When we compare the 147 publications focussing on BD agriculture with the number referring to Organic Agriculture (5498) and Integrated Agriculture (6676), we deduct that the research effort into BD agriculture carried out is indeed at an early stage of development. Of the total of 147 articles reporting to a broad extent studies on BD agriculture, 82 resulted in $\mathrm{IF} > 2$ and 68 (46% of the total) belonged to the first quartile of the corresponding WoS category.

The worldwide geographical distribution and focus on the Mediterranean area of articles published on peer-reviewed journals indexed on the Web of Science™ (WoS) Core Collection database from 1985 until 2018 are reported in Fig. 2. Most of the studies in the articles published on BD agriculture were carried out by institutions located in Europe: 54% were conducted in North and Central Europe (Germany, Sweden, Switzerland, Netherlands, UK, Ireland, Lithuania, Czech Republic, and Austria), 12% in Italy, and 6% in other

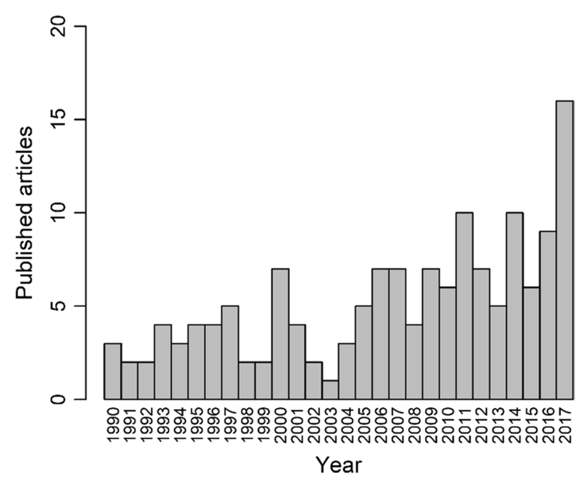


**Fig. 1** Total number of articles on biodynamic agriculture published in peer-reviewed journals indexed on the Web of Science.™ (WoS) Core Collection database from 1985 until 2017. Articles published before 1990 were not found in the database

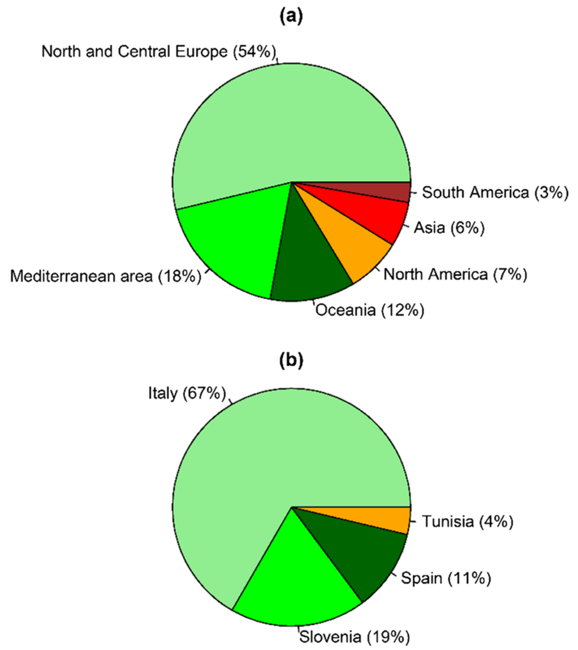


**Fig. 2** Worldwide geographical distribution (**a**) and focus on the Mediterranean area (**b**) of the articles published in peer-reviewed journals indexed on the Web of Science.™ (WoS) Core Collection database from 1985 until 2017

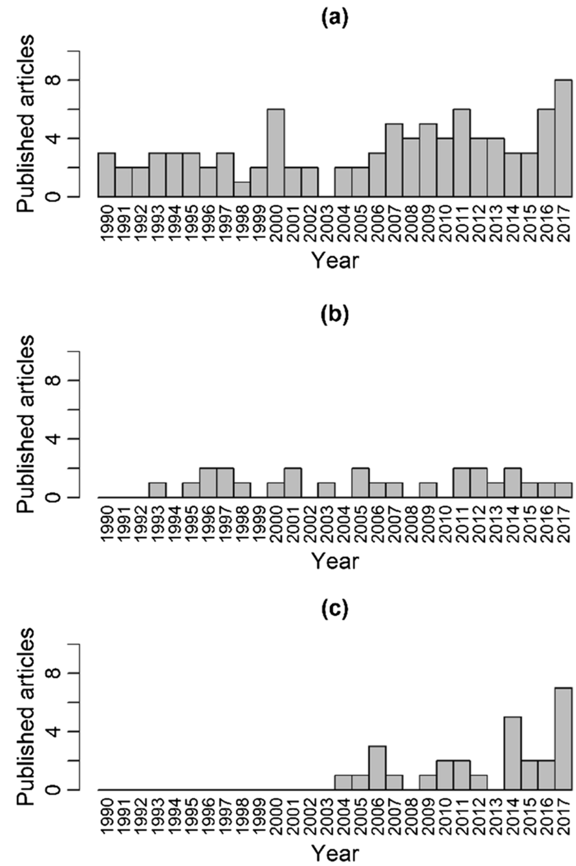


**Fig. 3** Number of the articles published in peer-reviewed journals indexed on the Web of Science.™ (WoS) Core Collection database from 1985 until 2017 grouped by three topics, i.e., biodynamic agricultural practices (**a**), sustainability of the biodynamic method (**b**), and food quality of biodynamic product (**c**)

Mediterranean countries (Spain, Slovenia, and Tunisia); 12% of research was carried out in Oceania (Australia, New Zealand), 7% in North America (USA, Canada), 6% in Asia (India, Philippines), and 3% in South America (Brazil, Venezuela).

The amounts of articles published on three major themes regarding BD agriculture, i.e., biodynamic agricultural practices (a), sustainability of the biodynamic method (b), and food quality of biodynamic products (c), are shown in Fig. 3. The number of articles referring to BD agriculture practices, sustainability, and food quality amounted to 93, 26, and 28, respectively (i.e., 63.3, 17.7, and 19.0%). Moreover, sustainability and food quality articles never exceeded two publications per year, with many years featuring no publications at all. Studies regarding food quality are exclusively recent, with the first publication in IF journals in 2004.

## Result of the literature survey on biodynamic agricultural practices

It is not easy to draw generic, globally valid conclusions on the impacts of BD agricultural practices based on such a small number of publications (93). However, a few tentative considerations can be made based on consolidated outcomes published in important publications since the 1990s, although only in reference to specific pedo-climatic and production conditions.

There are 42 articles within the "BD practices" topic belonging to the first quartile of the corresponding WoS category and with IF > 2. Articles presenting generic results as broadly as possible applicable to corresponding production systems (i.e., arable cropping and horticulture, viticulture, and olive tree cropping) were selected for further analysis. Our concern was to cover as many production systems as possible and consider those publications that produced generically applicable results. The selection of most informative publications on the impacts of BD practices is shown in Table 2 together with geographical location of the trials, trial description and duration, duration of the single experiments, size of experimental plots or samples, and parameters employed to assess the impacts of BD practices.

Most articles included in the BD practices group refer to aspects of soil quality. As reported by Mäder et al. (2002), BD practices, which primarily make use of preparation 500, improve the overall soil quality. Reganold et al. (1993, Table 3), comparing 16 BD and conventional farms in New Zealand, found that BD farms had better soil quality than conventional ones. In BD farms, significantly higher organic matter content and microbial activity, earthworm abundance and infiltration rate, better soil structure, aeration and drainage, and lower bulk density as well as thicker topsoil were found.

Several selected articles focus on outcomes from the well-known, 40-year-old DOK trial, which were published between 1993 and 2017 in highly ranked journals like "Science." These articles report on long-term comparisons between biodynamic, organic, and two conventional arable cropping systems. Based on the outcomes of the experiment in Therwil, Switzerland (Table 2, Therwil-1), the authors conclude that organically manured, legume-based crop rotations utilizing organic fertilizers from the farm itself are a realistic alternative to conventional farming systems. As regards soil aggregate stability, soil pH, stable organic matter formation, soil calcium and magnesium, microbial and faunal biomass (earthworm, carabids, staphylinids, and spiders), the BD system demonstrated the potential to be superior, under given circumstances, even as compared to the organic system (Mäder et al. 2002).

In a later study in the DOK trial (Table 2, Therwil-1), Fließbach et al. (2007) found that soil pH, total soil N, and soil organic carbon are higher in BD systems as compared to conventional systems. In addition, soil microbial biomass, soil organic matter for microbial biomass establishment, and dehydrogenase activity are higher in BD systems, indicating better soil quality in BD systems. In this article, it was also found that the metabolic quotient for $CO_2$ ($qCO_2$), which summarizes microbial carbon utilization, was higher in conventional as compared to BD soils, suggesting a higher maintenance requirement for microbial biomass in conventional soils. However, as regards soil microbial biomass C/N ratio (Cmic-to-Nmic), which is an indicator of biological soil fertility (Sparling 1992; Stockfisch et al. 1999), a treatment with compost and BD preparations reported lower performances as compared to a conventional manured system. The authors were unable to say whether this effect was caused by composting or by the BD preparations. This trend was not confirmed by Gadermaier et al. (2012) who stated that BD preparations increased the Cmic-to-Nmic in the Frick long-term experiment in Switzerland (Table 2).

From these studies, some additional conclusions can be drawn in terms of impact on agroecosystem biodiversity. The research carried out by Mäder et al. (2002) stated that BD preparations positively impact biodiversity. Moreover, Rotchés-Ribalta et al. (2017), in a study carried out in the DOK trial (Table 2, Therwil-1), found that weed seedbank abundance, diversity, and community composition were higher in the BD systems as compared with those of the conventional systems. They also found that high inputs of mineral fertilizers selected for more nitrophilous species, while herbicide applications selected against herbicide-susceptible species.

Crop yields are influenced by agricultural practices, and much research has focused on studying the differences between organic and conventional agriculture. However, only a few studies take into consideration BD agriculture. Among them, studies regarding arable cropping systems confirm that mean crop yields in BD farming are lower than those of conventional systems (Mäder et al. 2002; Mayer et al. 2015). While this is a common outcome of much research comparing yields of BD agriculture and also organic farming in many productive sectors, it is worth mentioning that higher yields are more often than not a result of higher input use which comes with a monetary but also with an energy and an ecological cost, as is more extensively remarked in the section below. Yield differences between organic and BD farming were surveyed by Zikeli et al. (2017) in a study of ten BD and organic greenhouses in Southern Germany. In this study, the BD farms had statistically significant

**Table 2** A selection of the most informative publications on the impacts of biodynamic practices

| Location of the trial | Trial description | Trial duration | Years of experiment | Size of experimental plots or samples | Parameter to assess BD[a] practices | References |
|---|---|---|---|---|---|---|
| Therwil-1, Switzerland | Long-term field trial ("DOK" trial)—system comparison between biodynamic, organic, two conventional and one control (unfertilized) in arable cropping systems | 1978–the present day | 21 years | 100 $m^2$ | Soil aggregate stability, soil pH, stable organic matter formation, soil calcium and magnesium, microbial and faunal biomass, grain yield, energy use and efficiency | Mäder et al. (2002) |
| | | | | 100 $m^2$ | Soil organic carbon, soil pH, total soil nitrogen, soil microbial biomass, soil microbial activity, soil dehydrogenase activity, soil basal respiration | Fließbach et al. (2007) |
| | | | 1 year | 100 $m^2$ | Weed seedbank abundance, diversity, and community composition | Rotchés-Ribalta et al. (2017) |
| Therwil-2, Switzerland | Long-term field trial ("DOK" trial)—system comparison between biodynamic, organic, two conventional systems using mineral fertilizers and farmyard manure at two fertilization intensities (50% of standard fertilization and standard fertilization) in winter wheat (*Triticum aestivum L.*) | 1978–the present day | 7 years | 100 $m^2$ | Crop yields, baking quality parameters, nitrogen use efficiency, effect of maize and potatoes as preceding crops | Mayer et al. (2015) |

**Table 2** (continued)

| Location of the trial | Trial description | Trial duration | Years of experiment | Size of experimental plots or samples | Parameter to assess BD[a] practices | References |
|---|---|---|---|---|---|---|
| Frick, Switzerland | Long-term field trial—effects of reduced tillage, organic fertilization strategies, and biodynamic preparations on organic grassland, pastures, and arable crop | 2002–the present day | 6 years | 144 $m^2$ | Soil organic carbon, soil microbial biomass, soil microbial activity, soil nutrients, soil nutrient budgets | Gadermaier et al. (2012) |
| Baden-Württemberg, Germany | 10 organic horticultural farms (5 biodynamic and 5 organic) | n.a.[c] | 3 years | Soil samples | Plant available phosphorus, soil potassium, soil organic carbon, soil pH, soil salinity | Zikeli et al. (2017) |
| Geisenheim, Germany | Long-term field trial—system comparison between integrated, organic, and biodynamic vineyards | 2006–the present day | 3 years | 216 $m^2$ | Plant growth response, physiological performance, yield, soil nutrient status, disease incidence, wine grape quality | Döring et al. (2015) |
| | | | 1 year | 216 $m^2$ | Soil fungal and bacterial biodiversity | Hendgen et al. (2018) |
| Wairau valley, New Zealand | Field crop trial comparison between six conventional and six biodynamic vineyards | n.a.[c] | 1 year | Bark, fruit, and soil samples | Fungal diversity across vineyard habitats (bark, fruit, soil) | Morrison-Whittle et al. (2017) |
| Tebano, Italy | Long-term field trial—system comparison trial between organic and biodynamic grapevines | From 2008 to 2013 | 3 years | 84 $m^2$ | Plant physiological responses, characterization of biodynamic preparations | Botelho et al. (2016) |
| Sfax, Tunisia | Biodynamic olive-growing farm | The farm has been managed biodynamically for 15 years at the time of publication | 1 year | Soil samples | Bacillus spp. abundance and pathogenicity to lepidopterans and coleopterans | Blibech et al. (2012) |

**Table 2** (continued)

| Location of the trial | Trial description | Trial duration | Years of experiment | Size of experimental plots or samples | Parameter to assess BD[a] practices | References |
|---|---|---|---|---|---|---|
| Darmstadt, Germany | Long-term field trial—comparison between three different fertilizers: inorganic, composted farmyard manure, and composted farmyard manure with the addition of BDa compost and preparations in arable cropping systems | 1980–the present day | 1 year | 25 $m^2$ | Soil microbial community composition in terms of AMF[b] and saprotrophic fungal biomass | Faust et al. (2017) |
| Hopland, California (USA) | Composting of a grape pomace and manure mixture with and without BD[a] compost preparations. Water extracts of finished composts were then used to fertigate wheat seedlings (*Triticum aestivum L.*), with and without added inorganic fertilizer | n.a.[c] | 2 years | Compost and wheat seedlings samples | Chemical, physical, and biological analyses of the compost. Growth response of wheat seedlings to aqueous compost extracts | Reeve et al. (2010) |
| Lopez Island, Washington State (USA) | Treatment comparison between lime, BD[a] preparations and an untreated control on permanent pasture | The farm has been managed organically for over 38 years at the time of publication | 2 years | 225.7 $m^2$ | Forage yield and quality, soil pH, total soil C and N, soil microbial activity, farm economic and social sustainability | Reeve et al. (2011) |
| Rome, Reggio Emilia and Bolzano, Italy | Different commercial samples of BD[a] preparation 500 from three Italian producers | n.a.[c] | 2 years | BD[a] preparation samples | Microbiological characterization and biological activities of preparation 500 | Giannattasio et al. (2013) |

[a]Biodynamic; [b]Arbuscular mycorrhizal fungal; [c]Not applicable

**Table 3** A selection of most the informative publications on sustainability of the biodynamic method

| Sustainability domain | Location of the trial | Trial description | Length/years of experiment | Assessment method | References |
|---|---|---|---|---|---|
| Environment | Policoro, Italy | Long-term field trial—system comparison between two integrated and one biodynamic apricot orchard | 20 years | Life cycle assessment (LCA), energy analysis (EA) | Pergola et al. (2017) |
| | Leiro and San Amaro, Spain | Field trial—system comparison between biodynamic and conventional vineyards | 2 years | Life cycle impact assessment (LCIA), land competition (LC), human labor (HL) | Villanueva-Rey et al. (2014) |
| | Pivola, Slovenia | Long-term field trial—system comparison between conventional, integrated, organic, and biodynamic wheat and spelt production | 3 years | Ecological footprint, overall footprint per unit, sustainable process index, ecological efficiency of production | Bavec et al. (2012) |
| | Therwil and Burgrain, Switzerland | Two long-term field trials—system comparison between biodynamic, organic, and conventional/integrated systems ("DOK" trial); integrated intensive, integrated extensive, and organic systems ("Burgrain" trial) in arable cropping and forage production systems | DOK trial: 14 years<br>Burgrain trial: 5 years | Swiss agricultural life cycle assessment, life cycle inventory, life cycle impact assessment | Nemecek et al. (2011a) |
| | Therwil, Burgrain and Zollikofen, Switzerland | Three long-term field trials—system comparison between biodynamic, organic, and conventional/integrated systems ("DOK" trial); integrated intensive, integrated extensive, and organic systems ("Burgrain" trial); conventional plowing and no-till soil cultivation systems ("Oberacker" trial) in arable cropping and forage production systems | DOK trial: 14 years<br>Burgrain trial: 5 years<br>Oberacker trial: 6 years | Life cycle assessment (LCA) | Nemecek et al. (2011b) |

**Table 3** (continued)

| Sustainability domain | Location of the trial | Trial description | Length/years of experiment | Assessment method | References |
|---|---|---|---|---|---|
| Economic | North Island of New Zealand | 16 biodynamic and conventional farms including market garden (vegetables), pip fruit (apples and pears), citrus, grain, livestock (sheep and beef), and dairy | 4 years | Farms economic profitability through the MAF[a] | Reganold et al. (1993) |
| | Madhya Pradesh, India | Field trial system comparison between biodynamic, organic, and conventional cotton-soybean-wheat crop rotations | 4 years | Agronomic, economic, and ecological performance, gross margin of cotton, soybean, and wheat | Forster et al. (2013) |
| Social | USA | System comparison between biodynamic, organic, and conventional agriculture | n.a[b] | Bruno Latour's circulatory model | Ingram (2007) |
| | Ireland | Interview with six biodynamic farmers | n.a[b]—the interview was done in 2001 | Social analysis | McMahon (2005) |

[a]Models used by the New Zealand Ministry of Agriculture and Fisheries (1987–1991); [b]Not applicable

higher yields in tomatoes and cucumbers as compared to the organic farms. Despite higher yields from BD farms, authors found strong imbalances between organic and BD farms as regards nutrient flows, with high average surpluses for N, P, S, Ca, and Na, which could lead to risks of increased soil alkalinity and salinity. Moreover, BD farms showed a lower N use efficiency (NUE) and significantly lower concentrations of soil available P. These imbalances were also confirmed by Mayer et al. (2015) in a previous study in the DOK trial (Table 2, Therwil-2). In this study, the conventional farming system at half standard fertilization level had a better NUE than organic and BD systems. Furthermore, low organic fertilizer inputs lead to degradation of soil quality in organic as well as in conventional systems. The results showed that fertilization strategies in organic and BD farming systems are a focal point for developing new strategies to avoid long-term nutrient imbalances.

BD practices have been mainly tested in vineyard production systems. This is because in recent years, many wine farms have decided to convert to BD agriculture (Demeter and BDA Certification 2020). A recent study involving a long-term trial in vineyards found that the organic and the BD treatments showed higher soil nitrogen levels, which had been successfully ensured through cover crop management and compost addition (Döring et al. 2015). However, magnesium content in leaf tissues, an important parameter required for chlorophyll composition, was found to be significantly higher in the integrated treatment, while phosphorous and potassium contents did not show any relevant differences. This is in line with the findings of an article published in Nature Scientific Reports, which stated that 10 years of different management practices had not caused any major shifts in terms of physicochemical soil parameters, and the only parameter exhibiting relevant differences was magnesium, which was found to be lower in BD systems (Hendgen et al. 2018). However, in terms of microbial activity, soil under integrated management had a significantly reduced bacterial and fungal species richness as compared to organic. Organic and BD treatments were statistically indistinguishable from one another, and the additional input of BD preparations did not affect the fungal composition or richness as compared to the organic treatment. Fungal communities were also quantified in six conventional and six BD vineyards by Morrison-Whittle et al. (2017).

By analyzing samples from several different vineyard "habitats" (i.e., bark, fruit, and soil) with metagenomic techniques, they found significantly higher species richness in BD fruit and bark communities, but not in soil. However, in terms of types and abundance of fungal species, BD management had a significant effect on soil and fruit.

In terms of yields, an average yield reduction was also found in BD vineyard production systems as compared to in integrated systems, which amounted to −34% (Döring et al. 2015). This is probably due to plant health and disease incidence. Indeed, in this study, disease frequency of Botrytis was significantly increased in the BD treatment as compared to the integrated treatment where botryticides were applied. Furthermore, in a 3-year field trial in Italy, grape yields were found to not differ when comparing organic and BD treatments (Botelho et al. 2016), probably due to similar disease incidence levels. Botelho et al. (2016) also assessed physiological responses of grapevines to BD management and provided evidence of a strong stimulation effect of natural defence compounds in grape plants grown with BD preparations 500, 500 K, fladen, and 501. They found that BD management led to an increase in leaf enzymatic activities of chitinase and β-1,3-glucanase as compared with organic management. Chitinase and glicanase activities are typically correlated with plant biotic and abiotic stresses and associated with induced plant resistance. Finally, they also found that the application of BD preparations reduced stomatal conductance and leaf water potential which indicated a higher water use efficiency (Chaves et al. 2010) in biodynamically managed vineyards. This is in line with Döring et al. (2015), who asserted that organic and BD treatments show significantly lower assimilation rates, transpiration rates, and stomatal conductance as compared to the integrated treatment. A reduction in stomatal conductance was then associated with enhanced tolerance of vine plants toward biotic (Zeng et al. 2010) and abiotic stresses (Salazar-Parra et al. 2012).

In addition to the studies conducted on vineyards and arable cropping systems, our literature review found that a single article related to BD olive production in Tunisia (Blibech et al. 2012). Blibech et al. (2012) detected a high number of *Bacillus* species in olive groves managed with BD and organic methods. After Choudhary and Johri (2009), these authors then supposed that an environment rich in organic substrates and micro-niches could support a complex of microbial species, in turn promoting the proliferation of *Bacillus*. Given the entomopathogenic role of *Bacillus* for several insects responsible for olive tree pests, they argued that BD and organic practices promote the biocontrol of olive pests. This is the first study that showed the occurrence of *Bacillus* larvicidal strains in a BD olive tree farm that could be used in biological control programmes.

In addition to studies related to different production systems, we found studies dealing with single BD practices. Faust et al. (2017) found that, in a long-term field trial in Germany, the application of BD preparations did not give rise to any positive effects additional to those of composted farmyard manure fertilization. This is in line with Reeve et al. (2010), who report no differences in terms of pH, mineral elements, C/N ratio, $NO_3$-N, and $NH_4^+$-N between a BD compost and an untreated compost. However, in a later study, Reeve et al. (2011) stated that, under changing circumstances, both the Pfeiffer field spray and other BD preparations were found to be moderately effective in raising soil pH.

In terms of microbial activity, conflicting results are reported by Reeve et al. (2010) and Reeve et al. (2011). In the first study, they reported the occasional superiority of BD compost to untreated compost, but in the latter, no effect of BD compost was found. In addition, Reeve et al. (2011) found no effect on forage yield between fields treated with BD compost and with untreated compost but reported the occasional superiority of the impact of BD compost on wheat seedling height; results showed that a 1% extract of BD compost grew 7% taller wheat seedlings than a 1% extract of untreated compost did (Reeve et al. 2010).

According to our selection of articles, there are only two surveys based on the manner of action of BD preparations. Giannattasio et al. (2013) performed a microbiological characterization of preparation 500 and identified some of its biological actions. They found that it is rich in enzymatic-specific activities and exhibits a positive auxin-like activity on plants but had no quorum sensing-detectable signal and no rhizobial nod gene-inducing properties. Moreover, they found that preparation 500 is relatively low in leucine aminopeptidase activity (an enzyme involved in nitrogen cycling), but enzymatic analyses indicated a bioactive potential in the fertility and nutrient cycling contexts.

Another study aimed at characterizing the composition of BD preparations is that of Botelho et al. (2016), in which the concentrations of isopenthyl adenine, indole-3-acetic acid, and abscisic acid were below the detection limits. Moreover, the extremely low amount of plant regulators supplied by the BD preparations suggests that the hormonal mode of action proposed by Stearn (1976) is unlikely. This is in contrast with Giannattasio et al. (2013) who found that the indol-3-acetic acid activity and microbial degradation products qualify preparation 500 for possible use as soil biostimulants.

## Results of the literature survey on sustainability of the biodynamic method

There were 15 articles related to topic of the "sustainability of the BD method" (26) belonging to the first quartile of the corresponding WoS category and with IF > 2. The selection of most informative publications on the sustainability of the BD method is shown in Table 3 together with the geographical location of the trials, trial description, duration of the single experiments, and assessment method for measuring BD sustainability. Moreover, we classified sustainability based on the United Nations Millennium Declaration (2000) in which three domains of sustainability were distinguished: environmental, economic, and social sustainability. Most of the studies of the sustainability of the BD method are included in the environmental domain (8 studies), with there being only four and three studies respectively on economic and social sustainability. Having so few scientific studies on these topics available prevents us from drawing generic conclusions, especially if we consider that the vast majority of the studies mentioned do not show comparisons between different cultivation methods under a range of different influencing factors, such as soil type, climate or year of production, as can be argued from Table 3, where locations with corresponding pedo-climatic conditions, as well as years of experiments are reported.

### *Environmental sustainability*

Agri-food is one of the sectors that contributes most to environmental impact in terms of resource depletion, land degradation, gaseous emissions, and waste generation (Cellura et al. 2012). There are several methods for assessing the agricultural impact on the environment, but life cycle assessment (LCA) is the most commonly used method as regards BD agriculture and one of the most commonly used in general. With this method it is possible to assess the environmental burden caused by a product, a production process, or any activity for providing services (Curran 2008).

A decrease of environmental burden due to production activities measured with LCA was observed for BD viticulture in North-West Spain (Villanueva-Rey et al. 2014) and apricot production in Southern Italy (Pergola et al. 2017). Pergola et al. (2017) compared two integrated systems and one greenhouse managed under BD agriculture in an apricot orchard long-term field trial. They reported that BD practices led to higher environmental impacts due to the specific cultivation techniques used in BD greenhouse production. However, excluding the plantation phase from the analysis, the BD system consumed less energy and showed a favorable energy balance. Indeed, considering only cultivation operations, the production of 1 kg of integrated apricots required from 2.60 to 3.00 MJ $kg^{-1}$of energy, while the production of BD apricots required 1.32 MJ $kg^{-1}$. A lower environmental burden for BD production systems was also found by Villanueva-Rey et al. (2014) due to an 80% decrease in diesel input. This is in accordance with other studies (Alaphilippe et al. 2013; Bavec et al. 2012; Stavi and Lal 2013; Venkat 2012). In Bavec et al. (2012), a markedly reduced ecological footprint was found in organic and BD wheat and spelt production, mainly due to the absence of external production factors. When considering yields, the organic and BD systems had a reduced overall footprint per product unit and increased ecological efficiency of production.

Soil carbon sequestration is a measure to prevent against $CO_2$ increase in the atmosphere and slow global warming (Janzen 2004; Page et al. 2011). Pergola et al. (2017) confirmed that, due to the soil management techniques used, the BD system fixed about 45% of the total $CO_2$ produced in the production cycle, with specific reference to soil. This is in line with Fließbach et al. (2007, Table 2) who found in the DOK trial that the soil organic carbon of the BD system was maintained at the same level for over

21 years and showed a small gain. This result is confirmed also by Reganold et al. (1993) and Droogers and Bouma (1996) comparing conventional and BD systems in which soil organic matter was proven to be stable only in the BD farming systems.

According to Mäder et al. (2002), the energy to produce an organic crop dry matter unit was 20 to 56% lower than in conventional (Table 2). Indeed, nutrient input, energy, and pesticide were reduced by 34%, 53%, and 97%, respectively, in the organic systems, whereas mean crop yield was only 20% lower, indicating more efficient production. In addition, Nemecek et al. (2011a and 2011b) concluded that the environmental impacts per unit area were minimized in organic and low-input farming. However, resources and inputs (nutrients, water, soil) use efficiency is also necessary to implement environmental sustainability in farms. Indeed, the reduction of fertilizer use cannot be pushed too far without risking poor crop performance, and a minimum level of nutrient supply must be maintained to ensure good eco-efficiency (Nemecek et al. 2011b). This was also confirmed by Mayer et al. (2015), who found that, disregarding parameters of long-term soil sustainability, the conventional farming system at half standard fertilization displayed the best performance in terms of yields, crop quality, and efficiency.

### *Economic and social sustainability*

The lower BD yields are compensated for by higher prices for BD commodities and by additional subsidies (Nemecek et al. 2011b). Consumers are willing to spend more to acquire BD products (Bernabéu et al. 2007; ICEX, 2010) but, as suggested by the Greentrade marketplace (2006), the increasing number of farms shifting to BD agriculture will eventually lead to a steady convergence between conventional and BD prices.

In our review, there were only two articles focusing principally on economic sustainability and the economic profit derived from BD and conventional farming systems (Table 3).

Forster et al. (2013) considered economic performance in a cotton-soybean-wheat crop rotation in India. They found that soybean gross margin was significantly higher for the BD system (+8%) as compared to conventional system, and the slightly lower productivity of BD soybean was counterbalanced by lower production costs. However, this was not confirmed for wheat and cotton because of their low crop yield. The second study included in our literature selection was published by Reganold et al. (1993) and compared 16 BD and conventional farms in New Zealand. They found that the BD farms were just as financially viable on a per hectare basis as the conventional farms.

Besides results on the economic and environmental sustainability of the BD method, we also found interesting outcomes from a social perspective. Following sociologist Bruno Latour's circulatory model of scientific work (Latour 1999), Ingram (2007) argued in the Annals of the Association of American Geographers that forms of alternative agriculture such as BD agriculture based on the "Going Back to Nature" paradigm were and have been the result of a scientific process characterized by an ongoing exchange of knowledge between scientists and farmers. BD networks have continued to consider farmers, especially those rejecting mainstream agriculture, as their primary counterpart (Ingram 2007). This is also confirmed by McMahon (2005), who interviewed six BD farmers in Ireland. However, he also found that some BD farmers restrict communication with the rural community and do not want to communicate the spiritual aspects of their farming methods, building from this perspective boundaries between them and "the Others."

## Result of the literature survey on food quality of biodynamic products

There are 11 articles within the "food quality" topic (28) belonging to the first quartile of the corresponding WoS category and with IF > 2, with the first published in 2006 by Zörb et al. The selection of most informative publications on the food quality of BD products is shown in Table 4 together with the geographical location of the trials, trial description, BD relevant products, year of product harvest, size of experimental plots or samples, and parameters to assess food quality.

In Zörb et al. (2006), a metabolite profiling of wheat (*Triticum aestivum L.*) grains was analyzed based on a total of 52 compounds. Only eight showed significant differences between organic and conventional systems, and no differences were found between organic and BD systems. Furthermore,

**Table 4** A selection of the most informative publications on food quality of biodynamic products

| Location of the trial | Trial description | Products | Years of product harvest | Size of experimental plots or samples | Parameters for assessing food quality | References |
|---|---|---|---|---|---|---|
| Therwil, Switzerland | Long-term field trial ("DOK" trial)—system comparison between biodynamic, organic, two conventional and one control (unfertilized) systems | Wheat grains (*Triticum aestivum L.*) | 2003 | Samples | Sugars, sugar alcohols, amino acids, organic acids | Zörb et al. (2006) |
| Lenart, Slovenia | Field trial comparison between integrated, organic, biodynamic, and control (unfertilized) systems | Rapeseed (*Brassica napus L.* "Siska") seeds | 2009/2010 and 2011/2012 | 72 $m^2$ | Water, protein, oil, glucosinolate, fatty acid composition | Turinek et al. (2016) |
| Florence, Italy | Field trial comparison between biodynamic, and conventional systems under water stress or standard conditions | Chicory (*Cichorium intybus L.*) | 2006/2007 | Samples | Polyphenol content, antiradical activity | Heimler et al. (2009) |
| Darmstadt, Germany | Field trial comparison between conventional, organic, and biodynamic systems | Batavia lettuce (*Lactuca sativa L.* ssp. acephala L.) | 2008 | 6 $m^2$ | Yield, polyphenol content (flavonoids, anthocyans, hydroxycinnamic acids), antiradical activity | Heimler et al. (2012) |
| Pivola, Slovenia | Long-term field trial—system comparison between conventional, integrated, organic, biodynamic, and control (unfertilized) systems | Red beet (*Beta vulgaris L.* ssp. vulgaris Rote Kugel) | 2009 | 70 $m^2$ | Sugar, organic acid, total phenolic content, antioxidative activity | Bavec et al. (2010) |
| 14 states in Brazil and Europe | Organic, biodynamic, and conventional products | Purple grape juices | n.a.[a] | Samples | Volatile organic compounds | Granato et al. (2015) |
| Literature review | Organic, biodynamic, and conventional products | Purple grape juices | 1998–2016 | n.a.[a] | Chemical composition, functional properties | Granato et al. (2016) |

**Table 4** (continued)

| Location of the trial | Trial description | Products | Years of product harvest | Size of experimental plots or samples | Parameters for assessing food quality | References |
|---|---|---|---|---|---|---|
| Alghero, Mamoiada, Mores, and Santadi, Italy | Field trial comparison between three conventional and one biodynamic systems | Purple grape juices from cultivar "Cannonau" | 2015 | Samples | Microbial diversity on wine must | Mezzasalma et al. (2017) |
| Gelderland and Friesland/Groningen, Netherlands | Comparison between three organic, three biodynamic, and 24 conventional farms | Cow milk | 2011 | Samples | Fat content, protein, lactose, urea, unsaturated fatty acid, milk freezing point depression | Capuano et al. (2014a) |
| | | | | | Fatty acid profiling, chemometric modelling | Capuano et al. (2014b) |

[a]Not applicable

Mayer et al. (2015) found that the conventional farming system at half standard fertilization had higher crude protein than organic and BD systems with standard fertilization and that doubling organic fertilization in organic and BD systems did not allow for improving grain baking quality. No differences between organic and BD systems were reported in terms of protein fractions, unextractable polymeric protein, gliadin, and dry gluten contents.

In another field trial comparison, Turinek et al. (2016) investigated the composition of rapeseed (Brassica napus L.) seeds and found that BD and organic production systems positively influenced oleic fatty acid and oil content as compared to an integrated system. Conversely, the integrated system produced seeds with higher protein and water contents, as well as higher contents of linolenic, gadoleic, and hexadecadienoic fatty acids, due to mineral fertilizer application.

Other studies comparing different management systems including BD farming were conducted on horticultural crops to study chemical composition and corresponding food quality. In an experiment conducted in Italy, the antiradical activity of chicory (*Cichorium intybus L.*) proved to be higher under BD than under conventional systems (Heimler et al. 2009). Such findings concerning antiradical activity were not confirmed by a following study carried out on Batavia lettuce (*Lactuca sativa L.*) in which, however, a higher amount of polyphenols was found under BD management (Heimler et al. 2012). Significantly, higher amounts of flavonoids and hydroxycinnamic acids in BD lettuce were detected as well, which was not the case for chicory. This last aspect could indicate an effect of BD practice on secondary metabolites in lettuce.

In the abovementioned studies, the response of different crops to BD, organic and conventional management is not univocal and probably derives from several causes, including genetic characters and pedoclimatic conditions. Despite this, other studies report univocal outcomes in favor of BD agriculture, e.g., Bavec et al. (2010), who analyzed the chemical composition of red beet (*Beta vulgaris L.*) in a long-term field trial. They found that samples from BD plots had significantly higher total phenolic content, antioxidant activity, and malic acid content than samples from conventional plots, whereas total sugar content did not differ between production systems.

In terms of number of studies, wine is the most common product to feature in BD food quality literature. Morrison-Whittle et al. (2017) evaluated the concentrations of volatile thiols important for aroma and quality in wines and found that there was no difference between BD and conventional wines. This was in line with Döring et al. (2015), who assessed grape quality comparing three farming systems (integrated, organic, and BD vineyards) and found that fruit quality in terms of total soluble solids, total acidity, and pH during ripening was not affected by the management system. However, BD treatment showed a significantly higher content of primary amino acids in healthy berries during maturation compared to the integrated treatment. Many other studies have argued that organic and BD viticulture have little influence on grape composition (Danner 1985; Hofmann 1991; Kauer 1994; Linder et al. 2006; Reeve et al. 2005). However, there is a trend for organic and BD juices to present higher contents of bioactive compounds as compared to conventional counterparts (Granato et al. 2016), and it is possible to differentiate organic/biodynamic and conventional purple grape juice through measurement of volatile organic compounds by proton transfer reaction mass spectrometry (Granato et al. 2015). Nevertheless, these and other studies found that BD and organic juices have very similar quality traits (Granato et al. 2015, 2016; Reeve et al. 2005), which is in line with the findings of Parpinello et al. (2015) who reported that the chemical and sensory properties of organic and BD wines do not differ.

In terms of types and abundance of communities of fungal species in juice, Morrison-Whittle et al. (2017) found no differences between management systems. However, Mezzasalma et al. (2017) stated that natural berry microbiome could be influenced by farming management and pointed out that biodynamics had a consistent effect on the bacterial communities of berries and corresponding must.

Animal-derived food is another important topic for understanding how the cultivation method can influence the quality of food. Capuano et al. (2014b) carried out an analysis of milk fatty acid profiles with cows from conventional, organic, and BD farms and found that organic/biodynamic milk differed from conventional milk. This was confirmed in a second part of their study (Capuano et al. 2014a), which analyzed the bovine milk by Fourier-transform infrared (FTIR) spectroscopy.

## Discussion and conclusion

### Discussion of the biodynamic method

The aim of this review was to critically review the international scientific literature on BD agriculture as published in highly ranked journals, as well as to detect any lack of knowledge on relevant issues in agriculture. The results of the literature review showed that the BD method enhances soil quality and biodiversity, while no conclusion can be drawn regarding the socio-economic sustainability and food quality of BD products; further efforts needing to be made to implement knowledge of these aspects.

Despite its being impossible to carry out a meta-analysis due to the small amount of data available and the vast range of differing parameters considered in the literature, some conclusive, semi-quantitative considerations can be drawn. To this end, we carried out a pairwise comparison exercise based on the results of BD, organic, and conventional agriculture regarding a vast range of parameters as published in highly ranked journals (IF > 2 and belonging to the first quartile of WoS corresponding categories). The results of pairwise comparison are shown in Table 5.

The pairwise comparisons regarding the impact of agricultural practices showed that from a total of 74 observations comparing differences between BD and organic farming, 22 observed better performance from BD agriculture, 37 found equal performance, and 15 found better performance from organic agriculture. The comparison of BD and conventional farming showed that 44 observations found BD agriculture performed better, 12 found they performed equally well, and 14 found conventional agriculture performed better. Finally, comparisons between organic and conventional farming showed that 33 observations found organic agriculture performed better, 13 found equal performance, and 11 found conventional agriculture performed better.

In terms of the sustainability of the BD method, the pairwise comparisons between BD and organic farming showed that one observation found in favor of BD agriculture, 24 found equal performance and two found in favor of organic agriculture, while the comparison between BD and conventional farming showed that 28 observations found BD performed better while seven found conventional agriculture did. Finally, the comparison between organic and

**Table 5** Results of pairwise comparison between biodynamic/organic, biodynamic/conventional, and organic/conventional production systems grouped by three topics, i.e., impact of agricultural practices, sustainability, and food quality. + and − values were attributed based on counting of pairwise comparisons carried out in the literature for all the criteria reported in the first row of the table. The results of pairwise comparisons were standardized on a −1/+1 scale, which was then transformed into five levels of performance ranging from − −, −, =, + and + +. It must be stressed that the majority of publications reporting ORG/CON comparisons in the overall literature do not encompass corresponding comparisons with BD agriculture; hence, the subset of comparisons upon which this table is based does not represent the entirety of ORG/CON comparisons in the literature

| | Impact of agricultural practices | Sustainability | Food quality |
|---|---|---|---|
| BD vs OR | =[c] | =[c] | =[c] |
| BD vs CO | + BD[d] | + + BD[e] | + BD[d] |
| OR vs CO | + OR[d] | + + OR[e] | =[c] |

[a] − −, Highly worse performance; [b] −, Worse performance; [c] =, Neutral result; [d] +, Better performance; [e] + +, Highly better performance

*BD*, biodynamic agriculture; *OR*, organic agriculture; *CO*, conventional agriculture

conventional farming showed that 22 observations found organic performed better and four found conventional agriculture did.

As regards the food quality of BD products, the pairwise comparisons between BD and organic farming showed that three observations found in favor of BD agriculture while 20 found equal performance. The comparison between BD and conventional farming showed that 13 observations found BD agriculture performed better, eight found no difference and seven found conventional agriculture performed better. Finally, the comparison between organic and conventional farming showed that four observations found organic agriculture performed better, 13 found no difference and four found better results from conventional agriculture.

It must be stressed that the majority of publications reporting organic/conventional comparisons in the overall literature do not examine BD agriculture; hence, the subset of articles cited in this manuscript does not represent the universe of organic/conventional comparisons in the literature, which greatly reduces the possibility of drawing generic conclusions in this matter. We have in any case reported the results of organic/conventional comparisons in BD agriculture publications as a reference for other comparisons within the set of publications analyzed in this article.

BD agricultural practices promote overall agroecosystem biodiversity. BD farms usually maintain vegetative buffer strips, riparian corridors and hedgerows that provide shelter to pollinators and natural predators. Indeed, the Biodiversity Farm Programme imposed by Demeter Standards obliges 10% of total farm area to be dedicated to the care of biodiversity, which includes elements for the maintenance of rare or endangered plant and animal species, creating optimal conditions for insects, birds and in general all lifeforms, including soil microorganisms. One of the major challenges for all production methods is to provide enough nutrients to plants while promoting overall soil quality. To this aim, BD agriculture promotes close cycles using farm-produced animal and green manure instead of employing external organic fertilizer. Indeed, it is a general principle required by BD standards to include the animal element in any farming system to avoid imports of organic inputs and related nutrient imbalances. By contrast, in some cases such as those reported by Zikeli et al. (2017), high intensification of production in greenhouse systems backed by minimum compliance of BD standards led to strong imbalances in nutrient cycles. However, it should be noted that cases like those described by Zikeli et al. refer to unique production conditions in intensive horticultural systems subject to the exceptional derogation offered to smallholders.

The combined effects of biodiversity management and nutrient cycling practices in BD agroecosystems seem to hold the potential to enhance soil microbioma. In our review, we found that overall microbial activity increased in BD farming systems as compared to conventional and organic agriculture (Mäder et al. 2002; Fließbach et al. 2007). This was also confirmed by a recent meta-analysis by Christel et al. (2021), which found that 52% of microbial indicators were higher even in comparison with organic farming. In this article, BD farming appears as the farming system with the most favorable effect on soil ecological quality, followed by organic and, finally, conventional farming. This is in line with previous studies by and Droogers and Bouma (1996), who found that organic matter contents were higher in BD as compared to conventional fields. However, microbial activity and proliferation could be influenced not only by the farming system but also by differing supply of organic substrate, water availability, climate, and by the absence of pesticides. Overall, one of the most important issues to be addressed and promoted among farmers, whatever farming method they adopt, is that soil acts as a habitat for many living organisms that supply a vast range of ecosystem services including soil fertility, and that the maintenance of healthy soil is vital to fulfill the needs of those microbial populations.

The third relevant aspect regarding the impact of agricultural practices focuses on the use of BD preparations (Table 1). Turinek et al. (2009) reviewed the effects of BD preparations on yield, soil quality, and biodiversity and came to the conclusion that the natural science mechanistic principle backing BD preparations is still unclear and needs further investigation. Beyond a scarcity of information on BD preparations, our selection of articles reports conflicting results, which does not allow us to draw generic conclusions on related potential benefits. However, two studies not included in our selection suggest that preparation 500 could have the potential to stimulate plant growth (Spaccini et al. 2012) and that cow horns in which bovine fecal material is incubated for several months, could provide suitable substrates for a specific proteolytic decomposition process (Zanardo et al. 2020). Further studies are needed to test the activity of BD preparations under different conditions.

The amount of selected articles on the sustainability of the BD method is notably low, which hinders the possibility of reaching robust conclusions. Most outcomes found in the literature on the sustainability of BD agriculture concern the environmental aspects, while socio-economic considerations are scarcely considered. Indeed, the results of the pairwise comparisons which focused exclusively on environmental sustainability showed that, from a total of 21 observations comparing the difference between BD and organic farming, one observation found in favor of BD agriculture, 19 found no difference and one found in favor of organic agriculture. The comparison between BD and conventional farming showed that 24 observations found BD to be better while 4 found for conventional agriculture. Finally, the comparison between organic and conventional farming showed that 19 observations found in favor of organic and two in favor of conventional agriculture. Hence, as regards environmental sustainability, there appears to be robust evidence in the literature of the fact that BD agriculture greatly outperforms conventional agriculture, while no difference has been detected as compared to the performance of organic agriculture.

At the farm economics level, our review confirms that remuneration of BD farmers appears to be equal or even considerably more profitable on a per hectare basis than conventional farming. This was confirmed on a national scale by the 2019 Bioreport published by the Italian Ministry of Agriculture, which stated that the turnover per hectare of Italian BD farms was in general higher as compared to conventional farms (i.e., 13.300 versus 3.207 euro/ha, Rete Rurale Nazionale 2019), and also by Penfold et al. (1995) who reported that BD system had the highest gross margins as compared to conventional, organic, and integrated systems. This might also be due to lower production costs and supply of wider range of goods and services producing income diversification in BD farms (Mansvelt et al. 1998). On the other hand, Aare et al. (2020) found that extra costs connected to diversification in BD farms do not generally pay off on standard food markets because of equal prices of organic and BD products, which leads BD farmers to export their products to countries like Germany and France where they can achieve 20% higher prices on average.

Finally, the results of the review of literature on social sustainability regard only two publications and are thus wholly insufficient to allow any generic conclusions on BD agriculture.

As regards the impact on food quality, BD agriculture performs slightly better than conventional while no difference was detected when comparisons between BD and organic were carried out. Though the food quality of BD products is at an early stage of development in the literature, some general remarks can be made concerning BD agriculture performances in relation to nutritional properties, which are the most frequently addressed topic in the scientific literature on the quality of food from BD agriculture. The outcomes of our review show BD products to be nutritionally richer than conventional counterparts. Other studies not included in our selection confirmed that nutritional properties, in particular the content of phenolic compounds, flavonoids, and antioxidant activity were significantly higher in strawberries, mangoes, and grapes from BD farming as compared to conventional (respectively, D'Evoli et al. 2010;

Fonseca Maciel et al. 2011; Reeve et al. 2005). However, dietary health is not only a matter of the nutritional value of food but also the result of how the soil microbiome interacts with plants, animals, and humans. Indeed, the concept of One Health proposes that there is a connection between human, animal, and environmental health (Karesh et al. 2012; Wolf 2015). Van Bruggen et al. (2019) argued that the health conditions of all organisms in an ecosystem are interconnected through the cycling of subsets of microbial communities from the environment (in particular the soil) to plants, animals, and humans. The One Health approach combined with better performances of BD soils in terms of microbial indicators as previously reported (Christel et al. 2021) might therefore support the idea that BD products are healthier.

### Need for a systemic approach

One frequent observation on the robustness of the results analyzed in this review of the literature regarding BD agriculture is that they can be greatly affected by production and site-specific conditions of relevant experiments. This aspect is common to all fields of research in agriculture but becomes, if possible, even more important when we investigate agroecological types of farming, including BD and organic agriculture. Systems theory holds that the behavior of any system in a hierarchy, e.g., the farm system, is not readily discoverable from a study of lower systems, e.g., cropping/livestock systems, and vice versa (Checkland 1981; Milsum 1972; Simon 1962; Whyte et al. 1969). The behavior of a system is instead a consequence of the combination of impacts of decisions taken at different levels in the hierarchy. Each level in the hierarchy could be related to any other, within and between levels (Conway 1987).

As a reaction against the reductionist approach which emphasizes the simplification of the system, agroecological thinking resulted in the development of an "agroecosystem" view (Conway 1987; Marten 1988), which promotes the need for a holistic and systemic approach to agroecosystems analysis. Systems theory (Bertalanffy 1968; Morin 1993; Odum 1989; Prigogine 1980) is an analysis method which describes interactions between components of the system and aims for a better understanding of system complexity. Any application of the theory of scaling should take into consideration the complex interactions between biophysical, social, economic, and institutional factors to analyze and understand the relations that characterize farming systems (Marchetti et al. 2020; Wigboldus et al. 2016). However, as reported by Schiller et al. (2019), limited analysis of how technological, political, and financial factors interact has been performed, and the evaluation of agroecosystem factors is complicated by their high dependence on the environmental and social conditions in which they are applied (Marten 1988). Current methods of analysis do not sufficiently consider system complexity and are based on the premise of "find out what works in one place and do more of the same in another place" (Wigboldus et al. 2016). Agricultural systems such as BD agriculture require more research based on a systemic approach which considers interconnections between ecological, economic, social, and political variables. A system thinking perspective on BD agriculture, as well as for other forms of agriculture, has to be conceptualized, and may serve as a basis for future research.

The best solutions for achieving a systemic approach for agroecological transitions might be found by integrating disciplines that explore the diversity and synergies of relationships between the various levels involved (Comeau et al. 2008; Ollivier et al. 2018; Wigboldus et al. 2016). This may require new expertise with the aim of facilitating collaborative processes (Brouwer et al. 2016; Hermans et al. 2013; Schut et al. 2011; Spruijt et al. 2014; Turnhout et al. 2013; Wigboldus et al. 2016; Wittmayer and Schäpke 2014). Moreover, as reported by Ollivier et al. (2018), beyond scientific disciplines, agroecological transition requires increasing knowledge through experiential and social learning processes within transdisciplinary epistemological research, involving farmers in all stages to cultivate new sustainable cultural approaches (Marchetti et al. 2020). It is necessary to innovate across all agri-food systems through forms of participatory research, which implies the involvement of farmers and consumers, and re-establishing producer–consumer connections.

While considering issues of experimental design, trials should minimize or eliminate confounding variables which can offer alternative explanations for the experimental results. For example, if BD and organic farmyard manure treatments are obtained from two different farms, differences could be caused not only by the biodynamic preparations but also by the different manure qualities (Heinze et al. 2010). Finally, as suggested by several authors (Bàrberi et al. 2010; Perry 1997), it is important that the experimental design includes large plots ensuring adequate replication in trials to avoid methodological spatial problems linked to heterogeneity of site-specific conditions.

In conclusion, BD agriculture offers promising contributions for the future development of sustainable agricultural production and food systems, but the extent to which relevant results can be considered scientifically reliable depends on a systemic and participatory approach being applied when addressing real-world business challenges.

## Concluding remarks

Scientific research into BD agriculture seems still to be at too early a stage of development to allow for reasonable, generic conclusions about its performance as a production method. All the topics so far analyzed need further study in order to allow relevant conclusions about different pedo-climatic, production and even cultural conditions to be made. Nevertheless, some tentative conclusions can be drawn. The results of the literature review showed that the BD method enhances soil quality and biodiversity. Many of these results were generated in long-term trials where the temporal dynamics of soil indicators could be studied. Further efforts need to be made, however, to understand the socio-economic sustainability and food quality aspects of BD products. One particularly promising topic of research consists in the assessment of microbial activity and the potential that the microbiome has in BD farms to enhance soil fertility and human health following the One Health approach. If such results could be obtained in BD agriculture by improving biodiversity management and nutrient cycling through animal rearing in farms or simply by applying BD preparations, the topic could be included in the research agenda. Moreover, it is critical to take a systemic approach to investigating similar subjects. We can therefore conclude that BD agriculture could provide benefits to the environment and that more research and innovation activities should be undertaken in order to provide additional information to farmers, policy makers, and stakeholders about this type of organic agriculture.

**Author contribution** The idea for the article was suggested by Prof. Gaio Cesare Pacini. The literature search and data analyses were performed by Dr. Lorenzo Ferretti. The draft of the manuscript was written by Dr. Margherita Santoni. The revision of the manuscript was carried out by Dr. Margherita Santoni, Prof. Gaio Cesare Pacini, Prof. Paola Migliorini, Dr. Lorenzo Ferretti, and Prof. Concetta Vazzana. All the authors read and approved the final manuscript.

**Funding** Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement.

**Data Availability** The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Code availability** The code generated and/or analyzed during the current study is available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.



## References

Aare AK, Egmose J, Lund S, Hauggaard-Nielsen H (2020) Opportunities and barriers in diversified farming and the use of agroecological principles in the Global North—the experiences of Danish biodynamic farmers. Agroecol Sustain Food Syst 45:390–416. https://doi.org/10.1080/21683565.2020.1822980

Alaphilippe A, Simon S, Brun L et al (2013) Life cycle analysis reveals higher agroecological benefits of organic and low-input apple production. Agron Sustain Dev 33:581–592. https://doi.org/10.1007/s13593-012-0124-7

Bàrberi P, Burgio G, Dinelli G et al (2010) Functional biodiversity in the agricultural landscape: relationships between weeds and arthropod fauna. Weed Res 50:388–401. https://doi.org/10.1111/j.1365-3180.2010.00798.x

Bavec M, Turinek M, Grobelnik-Mlakar S et al (2010) Influence of industrial and alternative farming systems on contents of sugars, organic acids, total phenolic content, and the antioxidant activity of red beet (Beta vulgaris L. ssp. vulgaris Rote Kugel). J Agric Food Chem 58:11825–11831. https://doi.org/10.1021/jf103085p

Bavec M, Narodoslawsky M, Bavec F, Turinek M (2012) Ecological impact of wheat and spelt production under industrial and alternative farming systems. Renew Agric Food Syst 27:242–250. https://doi.org/10.1017/S1742170511000354

Bernabéu R, Olmeda M, Castillo S, Díaz M, Olivas R, Montero F (2007) Determinación del sobreprecio que los consumidoresestán dispuestosa pagar porun vino ecológico en España. In: OIV World Congress. 10–16 July. Budapest, Hungary (in Spanish)

von Bertalanffy L (1968) General systems theory as integrating factor in contemporary science. Akten XIV Int Kongresses Für Philos 2:335–340. https://doi.org/10.5840/wcp1419682120

Blibech I, Ksantini M, Chaieb I et al (2012) Isolation of entomopathogenic *Bacillus* from a biodynamic olive farm and their pathogenicity to lepidopteran and coleopteran insect pests. Crop Prot 31:72–77. https://doi.org/10.1016/j.cropro.2011.09.020

Botelho RV, Roberti R, Tessarin P et al (2016) Physiological responses of grapevines to biodynamic management. Renew Agric Food Syst 31:402–413. https://doi.org/10.1017/S1742170515000320

Brouwer H, Woodhill AJ, Hemmati M, et al (2016) The MSP guide: how to design and facilitate multi-stakeholder partnerships

Capuano E, Van der Veer G, Boerrigter-Eenling R et al (2014) Verification of fresh grass feeding, pasture grazing and organic farming by cows farm milk fatty acid profile. Food Chem 164:234–241. https://doi.org/10.1016/j.foodchem.2014.05.011

Capuano E, Rademaker J, Van den Bijgaart H, Van Ruth SM (2014) Verification of fresh grass feeding, pasture grazing and organic farming by FTIR spectroscopy analysis of bovine milk. Food Res Int 60:59–65. https://doi.org/10.1016/j.foodres.2013.12.024

Cellura M, Longo S, Mistretta M (2012) Life cycle assessment (LCA) of protected crops: an Italian case study. J Clean Prod 28:56–62. https://doi.org/10.1016/j.jclepro.2011.10.021

Chaves MM, Zarrouk O, Francisco R et al (2010) Grapevine under deficit irrigation: hints from physiological and molecular data. Ann Bot 105:661–676. https://doi.org/10.1093/aob/mcq030

Checkland P (1981) Systems thinking, systems practice. Wiley, Chichester, UK

Choudhary DK, Johri BN (2009) Interactions of *Bacillus* spp. and plants—with special reference to induced systemic resistance (ISR). Microbiol Res 164:493–513. https://doi.org/10.1016/j.micres.2008.08.007

Christel A, Maron P-A, Ranjard L (2021) Impact of farming systems on soil ecological quality: a meta-analysis. Environ Chem Lett 19:4603–4625. https://doi.org/10.1007/s10311-021-01302-y

Comeau A, Langevin F, Caetano VR, et al (2008) A systemic approach for the development of FHB resistant germplasm accelerates genetic progress. Cereal Res Commun 36:5–9. https://www.jstor.org/stable/90003152

Conway GR (1987) The properties of agroecosystems. Agric Syst 24:95–117

Curran MA (2008) Life-Cycle Assessment. In: Jørgensen SE, Fath BD (eds) Encyclopedia of Ecology. Academic Press, Oxford, pp 2168–2174

D'Evoli L, Tarozzi A, Hrelia P et al (2010) Influence of cultivation system on bioactive molecules synthesis in strawberries: spin-off on antioxidant and antiproliferative activity. J Food Sci 75:C94-99. https://doi.org/10.1111/j.1750-3841.2009.01435.x

Danner R (1985) Vergleichende Untersuchungen zum konventionellen, organisch-biologischen und biolo- gisch-dynamischen Weinbau. Doctoral dissertation, Universität für Bodenkultur, Wien

Demeter and BDA Certification (2020). Demeter labelling, production and processing standard

Döring J, Frisch M, Tittmann S, Stoll M, Kauer R (2015) Growth, yield and fruit quality of grapevines under organic and biodynamic management. PLoS ONE 10(10):e0138445. https://doi.org/10.1371/journal.pone.0138445

Droogers P, Bouma J (1996) Biodynamic vs conventional farming effects on soil structure expressed by simulated potential productivity. Soil Sci Soc Am J 60:1552–1558. https://doi.org/10.2136/sssaj1996.03615995006000050038x

Faust S, Heinze S, Ngosong C et al (2017) Effect of biodynamic soil amendments on microbial communities in comparison with inorganic fertilization. Appl Soil Ecol 114:82–89. https://doi.org/10.1016/j.apsoil.2017.03.006

Fließbach A, Oberholzer H-R, Gunst L, Mäder P (2007) Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric Ecosyst Environ 118:273–284. https://doi.org/10.1016/j.agee.2006.05.022

Forster D, Andres C, Verma R et al (2013) Yield and economic performance of organic and conventional cotton-based farming systems—results from a field trial in India. PLoS ONE 8(12):e81039. https://doi.org/10.1371/journal.pone.0081039

Gadermaier F, Berner A, Fliessbach A et al (2012) Impact of reduced tillage on soil organic carbon and nutrient budgets under organic farming. Renew Agric Food Syst 27:68–80. https://doi.org/10.1017/S1742170510000554

Giannattasio M, Vendramin E, Fornasier F et al (2013) Microbiological features and bioactivity of a fermented manure product (Preparation 500) used in biodynamic agriculture. J Microbiol Biotechnol 23:644–651. https://doi.org/10.4014/jmb.1212.12004

Granato D, de Carrapeiro M, M, Fogliano V, van Ruth SM (2016) Effects of geographical origin, varietal and farming system on the chemical composition and functional properties of purple grape juices: a review. Trends Food Sci Technol 52:31–48. https://doi.org/10.1016/j.tifs.2016.03.013

Granato D, Koot A, van Ruth SM (2015) Geographical provenancing of purple grape juices from different farming systems by proton transfer reaction mass spectrometry using supervised statistical techniques. J Sci Food Agric 95:2668–2677. https://doi.org/10.1002/jsfa.7001

Greentrade marketplace (2006) Vinos ecológicos de alta calidad, comercio justo y precios estables. Notas de prensa de BioFach (in Spanish). http://www.greentrade.net/Articles135.html (accessed 19.03.13.)

Heimler D, Isolani L, Vignolini P, Romani A (2009) Polyphenol content and antiradical activity of Cichorium intybus L. from biodynamic and conventional farming. Food Chem 114:765–770. https://doi.org/10.1016/j.foodchem.2008.10.010

Heimler D, Vignolini P, Arfaioli P et al (2012) Conventional, organic and biodynamic farming: differences in polyphenol content and antioxidant activity of Batavia lettuce. J Sci Food Agric 92:551–556. https://doi.org/10.1002/jsfa.4605

Heinze S, Raupp J, Joergensen RG (2010) Effects of fertilizer and spatial heterogeneity in soil pH on microbial biomass indices in a long-term field trial of organic agriculture. Plant Soil 328:203–215. https://doi.org/10.1007/s11104-009-0102-2

Hendgen M, Hoppe B, Döring J, et al (2018) Effects of different management regimes on microbial biodiversity in vineyard soils. Sci Rep 8https://doi.org/10.1038/s41598-018-27743-0

Hermans F, Stuiver M, Beers PJ, Kok K (2013) The distribution of roles and functions for upscaling and outscaling innovations in agricultural innovation systems. Agric Syst 115:117–128. https://doi.org/10.1016/j.agsy.2012.09.006

Hofmann U (1991) Untersuchungen über die Umstellungsphase auf ökologische Bewirtschaftungssysteme im Weinbau im Vergleich zur konventionellen Wirtschaftsweise am Beispiel Mariannenaue—Erbach. Doctoral dissertation, Justus-Liebig-Universität Gießen

ICEX (2010) El mercado del vino ecológico en Alemania. Oficina Económica y Comercial de España en Düsseldorf (in Spanish)

Ingram M (2007) Biology and beyond: The science of "back to nature" farming in the United States. Ann Assoc Am Geogr 97:298–312. https://doi.org/10.1111/j.1467-8306.2007.00537.x

Janzen HH (2004) Carbon cycling in earth systems—a soil science perspective. Agric Ecosyst Environ 104:399–417. https://doi.org/10.1016/j.agee.2004.01.040

Karesh WB, Dobson A, Lloyd-Smith JO et al (2012) Ecology of zoonoses: natural and unnatural histories. Lancet Lond Engl 380:1936–1945. https://doi.org/10.1016/S0140-6736(12)61678-X

Kauer R (1994) Vergleichende Untersuchungen zum integrierten und ökologischen Weinbau in den ersten drei Jahren der Umstellung: Ergebnisse von 12 Standorten im Anbaugebiet Rheinhessen bei den Rebsorten Müller-Thurgau und Riesling. Doctoral dissertation, Justus-Liebig-Universität Gießen

Latour B (1999) Pandora's hope: Essays on the reality of science studies. Harvard University Press, Cambridge

Linder C, Viret O, Spring JL, Droz P, Dupuis D (2006) Viticulture intégrée et bio-organique: synthèse de sept ans d'observations. Revue Suisse Viticulture, Arboriculture, Horticulture 38:235–243

Fonseca Maciel L, da Silva OC, da Silva BE, da P. Spínola Miranda M, (2011) Antioxidant activity, total phenolic compounds and flavonoids of mangoes coming from biodynamic, organic and conventional cultivations in three maturation stages. Br Food J 113:1103–1113. https://doi.org/10.1108/00070701111180319

Mäder P, Fließbach A, Dubois D et al (2002) Soil fertility and biodiversity in organic farming. Science 296:1694–1697. https://doi.org/10.1126/science.1071148

Marchetti L, Cattivelli V, Cocozza C et al (2020) Beyond sustainability in food systems: perspectives from agroecology and social innovation. Sustainability 12:7524. https://doi.org/10.3390/su12187524

Marten GG (1988) Productivity, stability, sustainability, equitability and autonomy as properties for agroecosystem assessment. Agric Syst 26:291–316. https://doi.org/10.1016/0308-521X(88)90046-7

Masson P (2009) Biodinámica: guía práctica para agricultores y aficionados. Fertilidad de la Tierra, Estella, Navarra

Mayer J, Gunst L, Maeder P et al (2015) Productivity, quality and sustainability of winter wheat under long-term conventional and organic management in Switzerland. Eur J Agron 65:27–39. https://doi.org/10.1016/j.eja.2015.01.002

McMahon N (2005) Biodynamic farmers in Ireland. Transforming society through purity, solitude and bearing witness? Sociol Rural 45:98–114. https://doi.org/10.1111/j.1467-9523.2005.00293.x

Mezzasalma V, Sandionigi A, Bruni I et al (2017) Grape microbiome as a reliable and persistent signature of field origin and environmental conditions in Cannonau wine production. PLoS ONE 12(9):e0184615. https://doi.org/10.1371/journal.pone.0184615

Milsum JH (1972) The hierarchical basis for general living systems. In: Klir GJ (ed) Trends in General Systems Theory. Wiley, New York

Morin E (1993) Introduzione al pensiero complesso. Sperling & Kupfer, Milano

Morrison-Whittle P, Lee SA, Goddard MR (2017) Fungal communities are differentially affected by conventional and biodynamic agricultural management approaches in vineyard ecosystems. Agric Ecosyst Environ 246:306–313. https://doi.org/10.1016/j.agee.2017.05.022

Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G (2011) Life cycle assessment of Swiss farming systems: I. Integrated and Organic Farming Agric Syst 104:217–232. https://doi.org/10.1016/j.agsy.2010.10.002

Nemecek T, Huguenin-Elie O, Dubois D et al (2011) Life cycle assessment of Swiss farming systems: II. Extensive and Intensive Production Agric Syst 104:233–245. https://doi.org/10.1016/j.agsy.2010.07.007

Odum EP (1989) Ecology and our endangered life-support systems. Sinauer Associates Inc Mass. J Trop Ecol 6:202–202. https://doi.org/10.1017/S0266467400004338
Ollivier G, Magda D, Mazé A et al (2018) Agroecological transitions: what can sustainability transition frameworks teach us? An ontological and empirical analysis. Ecol Soc 23(2):5. https://doi.org/10.5751/ES-09952-230205
Page G, Kelly T, Minor M, Cameron E (2011) Modeling carbon footprints of organic orchard production systems to address carbon trading: an approach based on life cycle assessment. HortScience 46:324–327. https://doi.org/10.21273/HORTSCI.46.2.324
Parpinello GP, Rombolà AD, Simoni M, Versari A (2015) Chemical and sensory characterisation of Sangiovese red wines: comparison between biodynamic and organic management. Food Chem 167:145–152. https://doi.org/10.1016/j.foodchem.2014.06.093
Paull J, Hennig B (2020) A world map of biodynamic agriculture. In: Agric. Biol. Sci. J. https://orgprints.org/id/eprint/38129/. Accessed 18 Mar 2022
Penfold CM, Miyan MS, Reeves TG, Grierson IT (1995) Biological farming for sustainable agricultural production. Aust J Exp Agric 35:849–856. https://doi.org/10.1071/ea9950849
Pergola M, Persiani A, Pastore V et al (2017) A comprehensive life cycle assessment (LCA) of three apricot orchard systems located in Metapontino area (Southern Italy). J Clean Prod 142:4059–4071. https://doi.org/10.1016/j.jclepro.2016.10.030
Perry JN (1997) Statistical aspects of field experiments. In: Dent DR, Walton MP (eds) Methods in ecological and agricultural entomology. CABI Publishing, Wallingford, UK, pp 171–201
Prigogine I (1980) From being to becoming. W. H. Freeman, San Francisco
R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/
Reeve JR, Carpenter-Boggs L, Reganold JP et al (2005) Soil and winegrape quality in biodynamically and organically managed vineyards. Am J Enol Vitic 56:367–376
Reeve JR, Carpenter-Boggs L, Reganold JP et al (2010) Influence of biodynamic preparations on compost development and resultant compost extracts on wheat seedling growth. Bioresour Technol 101:5658–5666. https://doi.org/10.1016/j.biortech.2010.01.144
Reeve JR, Carpenter-Boggs L, Sehmsdorf H (2011) Sustainable agriculture: a case study of a small Lopez Island farm. Agric Syst 104:572–579. https://doi.org/10.1016/j.agsy.2011.04.006
Reganold JP, Palmer AS, Lockhart JS, Macgregor AN (1993) Soil quality and financial performance of biodynamic and conventional farms in New-Zealand. Science 260:344–349. https://doi.org/10.1126/science.260.5106.344
Rete Rurale Nazionale 2014–2020 (2019) Bioreport 2017–2018. L'agricoltura biologica in Italia. Rete Rurale Nazionale 2014–2020, Roma. https://www.reterurale.it/Bioreport201718
Rotchés-Ribalta R, Armengot L, Mader P et al (2017) Long-term management affects the community composition of arable soil seedbanks. Weed Sci 65:73–82. https://doi.org/10.1614/WS-D-16-00072.1
Salazar-Parra C, Aguirreolea J, Sanchez-Diaz M et al (2012) Photosynthetic response of Tempranillo grapevine to climate change scenarios. Ann Appl Biol 161:277–292. https://doi.org/10.1111/j.1744-7348.2012.00572.x
Schiller KJF, Klerkx L, Poortvliet PM, Godek W (2019) Exploring barriers to the agroecological transition in Nicaragua: a technological innovation systems approach. Agroecol Sustain Food Syst 44:88–132. https://doi.org/10.1080/21683565.2019.1602097
Schut M, Leeuwis C, van Paassen A, Lerner A (2011) Knowledge and innovation management in the policy debate on biofuel sustainability in Mozambique: what roles for researchers? Knowl Manag Dev J 7:45–64. https://doi.org/10.1080/19474199.2011.593874
Simon HA (1962) The architecture of complexity. Proc Am Philos Soc 106(6):467–482
Spaccini R, Mazzei P, Squartini A et al (2012) Molecular properties of a fermented manure preparation used as field spray in biodynamic agriculture. Environ Sci Pollut Res Int 19:4214–4225. https://doi.org/10.1007/s11356-012-1022-x
Sparling G (1992) Ratio of microbial biomass carbon to soil organic-carbon as a sensitive indicator of changes in soil organic-matter. Aust J Soil Res 30:195–207. https://doi.org/10.1071/SR9920195
Spruijt P, Knol AB, Vasileiadou E et al (2014) Roles of scientists as policy advisers on complex issues: a literature review. Environ Sci Policy 40:16–25. https://doi.org/10.1016/j.envsci.2014.03.002
Stavi I, Lal R (2013) Agriculture and greenhouse gases, a common tragedy. A Review Agron Sustain Dev 33:275–289. https://doi.org/10.1007/s13593-012-0110-0
Stearn WC (1976) Effectiveness of two biodynamic preparations on higher plants and possible mechanisms for the observed response. MSc thesis, Ohio State University, Columbus, Ohio
Steiner R, (1924) Impulsi scientifico spirituali per il progresso dell'agricoltura. Editrice Antroposofica srl, Milano, Italia
Stockfisch N, Forstreuter T, Ehlers W (1999) Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil Tillage Res 52:91–101. https://doi.org/10.1016/S0167-1987(99)00063-X
Turinek M, Grobelnik-Mlakar S, Bavec M, Bavec F (2009) Biodynamic agriculture research progress and priorities. Renew Agric Food Syst 24:146–154. https://doi.org/10.1017/S174217050900252X
Turinek M, Bavec M, Repic M et al (2016) Effects of intensive and alternative production systems on the technological and quality parameters of rapeseed seed (Brassica napus L. 'Siska'). J Sci Food Agric 97:2647–2656. https://doi.org/10.1002/jsfa.8088
Turnhout E, Stuiver M, Klostermann J et al (2013) New roles of science in society: different repertoires of knowledge brokering. Sci Public Policy 40:354–365. https://doi.org/10.1093/scipol/scs114
United Nations Millennium Declaration (2000). United Nations General Assembly resolution 55/2. https://www.ohchr.

org/en/instruments-mechanisms/instruments/united-nations-millennium-declaration. Accessed 19 Mar 2022
van Bruggen AHC, Goss EM, Havelaar A et al (2019) One Health—cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. Sci Total Environ 664:927–937. https://doi.org/10.1016/j.scitotenv.2019.02.091
van Mansvelt JD, Stobbelaar DJ, Hendriks K (1998) Comparison of landscape features in organic and conventional farming systems. Landsc Urban Plan 41:209–227. https://doi.org/10.1016/S0169-2046(98)00060-7
Venkat K (2012) Comparison of twelve organic and conventional farming systems: a life cycle greenhouse gas emissions perspective. J Sustain Agric 36:620–649. https://doi.org/10.1080/10440046.2012.672378
Villanueva-Rey P, Vazquez-Rowe I, Teresa Moreira MO, Feijoo G (2014) Comparative life cycle assessment in the wine sector: biodynamic vs. conventional viticulture activities in NW Spain. J Clean Prod 65:330–341. https://doi.org/10.1016/j.jclepro.2013.08.026
Whyte LL, Wilson AG, Wilson D (1969) Hierarchical structures. Elsevier Sci Publ, New York
Wickham H (2011) The Split-Apply-Combine strategy for data analysis. J Stat Softw 40:1–29. https://doi.org/10.18637/jss.v040.i01
Wigboldus S, Klerkx L, Leeuwis C et al (2016) Systemic perspectives on scaling agricultural innovations. A Review Agron Sustain Dev 36:46. https://doi.org/10.1007/s13593-016-0380-z
Willer H, Schlatter B, Trávníček J, et al (2020) The World of Organic Agriculture Statistics and Emerging Trends 2020. Research Institute of Organic Agriculture (FiBL) and IFOAM – Organics International, Frick and Bonn
Wittmayer J, Schäpke N (2014) Action, research and participation: roles of researchers in sustainability transitions. Sustain Sci 9(4):483–496. https://doi.org/10.1007/s11625-014-0258-4
Wolf M (2015) Is there really such a thing as “one health”? Thinking about a more than human world from the perspective of cultural anthropology. Soc Sci Med 129:5–11. https://doi.org/10.1016/j.socscimed.2014.06.018
Zanardo M, Giannattasio M, Sablok G, et al (2020) Metabarcoding analysis of the bacterial and fungal communities during the maturation of Preparation 500, used in biodynamic agriculture, suggests a rational link between horn and manure. https://doi.org/10.20944/preprints202008.0727.v1
Zeng W, Melotto M, He SY (2010) Plant stomata: a checkpoint of host immunity and pathogen virulence. Curr Opin Biotechnol 21:599–603. https://doi.org/10.1016/j.copbio.2010.05.006
Zikeli S, Deil L, Moeller K (2017) The challenge of imbalanced nutrient flows in organic farming systems: a study of organic greenhouses in Southern Germany. Agric Ecosyst Environ 244:1–13. https://doi.org/10.1016/j.agee.2017.04.017
Zörb C, Langenkamper G, Betsche T et al (2006) Metabolite profiling of wheat grains (Triticum aestivum L.) from organic and conventional agriculture. J Agric Food Chem 54:8301–8306. https://doi.org/10.1021/jf0615451