

Review Article

Organic and Biodynamic Viticulture Affect Biodiversity and Vine and Wine Properties: A Systematic Quantitative Review

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Abstract: Demand for organically grown crops has increased exponentially in the last few decades. Particularly in the wine sector, organic and biodynamic management systems are gaining more and more importance, with some of the most prestigious wineries converting to organic or biodynamic viticulture. The purpose of the study was to review evidence comparing effects of conventional, organic, and biodynamic viticulture on soil properties, biodiversity, vine growth and yield, disease incidence, grape composition, sensory characteristics, and wine quality. Only studies with representative field replicates or studies with a representative number of samples were included. Soil nutrient cycling was enhanced under organic viticulture especially after conversion was completed. Cover crop mixtures used, compost application as well as the absence of herbicides might be factors that account for higher biological activity in organically and biodynamically managed soils. 17 out of 24 studies observed a clear increase in biodiversity under organic viticulture on different trophic levels. Plant protection regime and

cover crop mixtures mainly determine higher biodiversity in organic and biodynamic viticulture. Organic and biodynamic treatments showed 21 % lower growth and 18 % lower yield compared to conventional viticulture. The decrease of growth and yield under organic and biodynamic viticulture was not correlated to the growth or yield level under conventional viticulture. A decrease in soil moisture content and physiological performance (assimilation rate, transpiration rate and stomatal conductance) under organic and biodynamic viticulture is likely to be responsible for the lower growth and yield in the respective management systems. Juice total soluble solids concentration did not differ among the different management systems. No overall differences in berry composition, juice or wine quality among management systems could be observed. By describing different hypotheses concerning the effects of organic and biodynamic viticulture, this review and meta-analysis provides helpful guidance for defining further research in organic agriculture on perennial, but also on annual crops.

Key words: biodiversity, cover crop, crop level, floor management, grape composition, vegetative growth, wine composition

Introduction

The production of organically grown crops develops exponentially in the last few decades based on consumer demands for healthy food as well as environmentally friendly farming practices (Yiridoe et al. 2005). Current agricultural and environmental policies are reacting to these demands with initiatives limiting the use of synthetic pesticides and thus promoting organic farming (Vidal and Kelly 2013, Wysling 2015, Kucera 2017). The controversial debate on the ban of glyphosate, main ingredient of Monsanto's best-selling herbicide "Roundup", in the EU has lately made organic farming the center of attention again (Neslen 2017).

The start of organic agriculture that developed almost independently in the German- and English-speaking world dates back to the beginning of the last century. The first movements towards organic farming were developed from a reaction to ecological and soil-related, but also economic and social problems that occurred during the two World Wars. Acidification of soils, loss of soil structure, soil fatigue, decrease of seed and food quality and an increase of plant and

animal diseases were attributed to the chemical-technical intensification of agriculture (Vogt 2000). In addition, yield levels in Germany decreased drastically in the 1920's in comparison to the years before World War I, even though the use of mineral fertilizers increased. The early movements towards organic agriculture focus on improved soil fertility while reducing the use of mineral fertilizers, and aim to create a more sustainable form of agriculture while still producing high quality crops. The different forms of organic agriculture have evolved with time and now incorporate knowledge about biologically stabilized soil structure, rhizosphere dynamics and systems ecology (Vogt 2000, 2007). Research on the respective management systems started mainly after World War II with the establishment of some long-term field trials comparing different agricultural management systems (Stinner 2007). In viticulture, organic and biodynamic management approaches were initially applied in the late 1960's with research on organic viticulture starting soon after (Danner 1985).

Land used for organic agriculture increased from 11 million hectares in 1999 to 43.7 million hectares in 2014, which is about 1 % of global agricultural land. At the same time the organic market size increased from 15.2 billion US dollars in 1999 to 80 billion dollars in 2014 (Lernoud and Willer 2016). Compared to total agriculture perennial cropland has a much higher share in organic management (Lernoud and Willer 2016). In viticulture, 316,000 hectares of grapes are grown organically, which is a 4.5 % share of the global grape growing area. Most of this organic grape growing area is located in Europe (266,000 hectares). The three countries with the largest organic grape growing area are Spain, Italy and France (Lernoud and Willer 2016). Eleven thousand two hundred hectares of vineyards for wine production worldwide are managed according to biodynamic principles or are in conversion to biodynamic viticulture (Castellini et al. 2017). The biggest international biodynamic association is Demeter. Particularly in the wine sector, organic and biodynamic management practices are gaining more importance, with some of the most prestigious wineries converting to organic or biodynamic viticulture (Reeve et al. 2005).

Food and Agriculture Organization (FAO) defines organic farming as follows: "Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It

emphasizes the use of management practices in preference to the use of off-farm inputs [...]. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfill any specific function within the system” (FAO 1999). In the European Union (EU) several regulations exist to control organic farming . In Appendix II of the latter there is a list of substances allowed in organic farming and thus organic viticulture. Any substance which is not on the list is forbidden. Furthermore there is a regulation outlining detailed rules on organic winemaking in the EU. There are also specific national rules, e.g. the restriction of copper (Cu) use in German viticulture to 3 kg/ha/year, and several organic or biodynamic associations which impose stricter rules than the EU standards (e.g. ECOVIN association in Germany imposes a maximum nitrogen input of 150 kg/ha/3 years and allows growers to plough the soil within rows without sowing cover crop for maximum three months during summer). In the United States (US) there are Organic Regulations by the US Department of Agriculture (USDA) controlling organic farming. The National Organic Program (NOP) develops rules and regulations for production, handling, labeling and enforcement of organic products (USDA organic regulations viewed on 04/18/17). In contrast to EU standards there is a National List of Allowed and Prohibited Substances in the US (USDA national list viewed at 04/18/17). Beyond that a lot of National Organic Farming Associations exist in the US. In Australia the Biosecurity section of the Department of Agriculture (Australia), formerly AQIS (Australian Quarantine and Inspection Service of the Department of Agriculture, Fisheries and Forestry of the Australian Government), is responsible for the accreditation of the national certifying bodies according to the National Standard for Organic and Bio-Dynamic Produce. Appendices of this National Standard contain lists of permitted materials in organic and biodynamic farming as well as the criteria to evaluate inclusion of inputs and additives in this standard (Organic industry standards and certification committee, 2015). As of 2015, there were seven approved certifying organizations in Australia. Besides these national control bodies there are several associations such as Biodynamic Agriculture Australia BAA or Demeter, that set stricter rules than the national legislation does. There is a transition period of 3 years in the US, EU and Australia for becoming a certified organic or biodynamic producer. The implementation

of regulations concerning the organic vineyard management is described by Provost and Pedneault (2016).

Biodynamic farming abides by the same regulations as organic farming. It is a holistic agricultural system based on the respect for the spiritual dimension of the living and inorganic environment (Vogt 2007). It was founded in 1924 by Rudolf Steiner and was one of the first movements towards organic agriculture (Steiner 2005). It should ideally be practiced on mixed farms including crops as well as livestock to meet the requirements of the farm as an organism raised by Steiner in his agricultural course (Steiner 2005). The application of specific biodynamic preparations is one key element of this management system (Leiber et al. 2006) and is one essential difference in comparison to organic farming. These substances are said to stimulate soil nutrient cycling, promote photosynthetic activity of the crops and compost transformation (Masson and Masson 2013). The field spray preparations horn manure and horn silica (Table 1) are diluted in water in very small quantities, stirred for one hour and then applied to soil or plants, respectively (Masson and Masson 2013). The compost preparations (Table 1) are applied to a compost and are said to facilitate the transformation process (Masson and Masson 2013). Each of the preparations is put into the compost in small quantities and the valerian preparation is sprayed over the compost heap (Masson and Masson 2013).

The aim of this meta analysis is to summarize the outcomes of scientific trials performed on organic and biodynamic viticulture worldwide and hence characterize the effects of the respective management systems. This review addresses the question of whether conventionally, organically and biodynamically managed vineyards differ in regards to soil properties, biodiversity, vine growth and yield, disease incidence, grape composition, wine quality, sensory characteristics and production costs. Qualitative results showing the overall effects of organic and biodynamic viticulture and quantitative results displayed as regression analyses of available datasets are presented. By describing and quantifying the effects of the respective viticultural management systems the review provides decision support for producers, consumers as well as researchers. In addition, new findings concerning the reasons for the effects of organic and biodynamic management in viticulture are described. Different hypotheses for explaining the

observed phenomena are presented. Therefore this review and meta-analysis also provides helpful guidance for defining future areas of research.

Published Data Sourcing and Selection

Literature searches of peer-reviewed published literature were conducted to find studies investigating organic and/or biodynamic viticulture. The following search terms were used in different combinations in the ISI-Web of Science and Pubmed Databases: organic/viticulture, biodynamic/viticulture, biodynamic/agriculture/grapes (last searched on 08/25/17).

Only field trials that used replicates of management treatments with representative plots or studies that used a representative number of samples were included in the review in order to avoid bias in individual studies. Data from non-peer-reviewed sources such as conference proceedings, master theses or doctoral dissertations were also included into this study if they met the criteria mentioned above. Also, in Germany and Austria some long-term studies were conducted between 1980 and 2015 whose results were published as doctoral theses in German language. These findings were translated and included. In Australia a long-term trial was conducted between 2009 and 2014 whose results were partially published as Honours and Master theses and results were included. Furthermore, unpublished data from the latter trial and from a long-term trial in Germany were provided by the authors and were included in the review and in the meta-analyses.

This led to a total number of 84 studies included in the review, of which 64 were peer-reviewed and 20 non-peer-reviewed.

Seventeen studies that met the criteria mentioned above and whose datasets were available were included into the quantitative meta-analyses. Data were extracted manually from the different studies. If different forms of conventional viticulture were included in the studies, low input conventional plots were chosen for meta-analysis. If compost was applied to the different plots, as was the case in the Australian long-term trial, means per treatment and year were calculated for plots with and without compost application. These treatment means were included in the meta-analysis. For the study by Linder et al. (2006) and by Wheeler and Crisp (2011) means per treatment over 8-year and 5-year periods, respectively, were available and

were included. Characteristics of the studies included in the meta-analyses and meta-regressions are presented in Supplemental Table 1.

Data Analysis

Linear meta-regression analyses were performed in order to evaluate the quality of the correlations of several parameters (growth, yield and total soluble solids in juice) between conventionally and organically or biodynamically managed vineyards. By meta-regression analyses the following questions were addressed: What is the magnitude of the effect of organic and biodynamic management on vine growth (expressed as pruning weight), vine yields and total soluble solids in juice?

To assess if conventional and organic/biodynamic viticulture differ in vine growth, vine yield and total soluble solids in juice and if the observed effects are consistent across all environments ANOVA and Tukey-Test (Post-Hoc-Test) was performed. The factors were treatment (conventional or organic including biodynamic), location of the study (America, Europe or Australia) and interactions between treatment and location were assessed. All statistics were carried out using the statistical software R (Ihaka and Gentleman 1996). For meta-regression analysis as well as for ANOVA and Post-Hoc-Test means per treatment, year and variety were calculated in order to avoid bias among studies due to differing number of plots or vineyards.

For all studies considered in the meta-analyses and meta-regressions, effects and variance were estimated (S1-S3 Figs). Studies are partially heterogenic, especially concerning the pruning weight, are limited in number and publication bias cannot be excluded.

Management Effects on Soil

The improvement of soil fertility without any synthetic nitrogen fertilizers is a key principle of organic farming. The most important source of nitrogen as well as other nutrients in organic farming is the use of compost. It supplies the soil with organic nitrogen which has to be converted into inorganic nitrogen compounds to be taken up by the plants (Kauer 1994, Vogt 2007). Therefore the stimulation of soil nutrient cycling plays a major role in organic farming as

well as in organic viticulture to supply the plants with inorganic nutrients. The biological activity of the soil and the feeding activity of soil organisms are reported to increase under organic and biodynamic viticulture in comparison to conventional management (Gehlen et al. 1988, Reinecke et al. 2008, Okur et al. 2009, Freitas et al. 2011) (Table 2). The contents of organic C, total N, P and S do not differ among treatments (Wheeler 2006, Probst et al. 2008, Collins et al. 2015b). In contrast, P contents in the soil were reported to rapidly decrease after conversion in a long-term field trial in Southern France. After seven years of conversion authors observed a gradual increase of available P contents under organic management (Coll et al. 2011). Biodynamic and organic vineyards show a higher cumulative soil respiration, a higher content of microbial biomass C and a higher ratio of microbial biomass C to organic C, especially after conversion (Gehlen et al. 1988, Probst et al. 2008, Okur et al. 2009, Coll et al. 2011, Freitas et al. 2011, Collins et al. 2015b). In one study conducted in Southern France soil organic matter and potassium content were increased under organic viticulture (Coll et al. 2011). One reason for the increased contents of P and K in the soil under organic viticulture could be the increased microbial activity and the increased microbial biomass (Coll et al. 2011). In addition, organic and biodynamic treatments show lower $q\text{CO}_2$ values (Probst et al. 2008, Freitas et al. 2011). Low $q\text{CO}_2$ levels indicate high microbial substrate-use efficiency (Probst et al. 2008). This is in accordance with the results of Mäder et al. (2002) who showed that higher microbial substrate-use efficiency in combination with a higher availability of soil organic matter to soil microorganisms are a characteristic result of organic farming. Yet indicators of microbial activity in the soil are strongly dependent on the vineyard location and its management. The positive effects of organic and biodynamic vineyard management on soil microbial properties are reported to increase together with the time-span since conversion (Probst et al. 2008, Coll et al. 2011). Mineralized nitrogen content in the topsoil layer did not differ among organic, biodynamic and integrated viticulture in a field trial in Germany in the first three years of conversion (Meißner 2015). Integrated farming is an approach which promotes sustainable farming by using all possible tools and techniques to reduce input of chemicals. Polluting inputs are minimized and resources are used sustainably (Ente Nazionale Italiano di Unificazione 2009). In the same trial mineralized nitrogen content in the topsoil layer was reported to increase

under organic and biodynamic management after the first four years of conversion (Döring et al. 2015). This implies that stimulation of soil nutrient cycling by compost application, the implementation of cover crop mixtures with a wide range of species including legumes and denial of mineral fertilizers, as practiced in the organic and biodynamic treatments, takes some years to make an impact on nitrogen levels and on microbial activity in the soil. This again is in accordance with other findings concerning soil microbial properties under organic management (Coll et al. 2011). As mentioned above, microbial biomass C also increased under organic and biodynamic viticulture after conversion in a long-term field trial in Australia (Collins et al. 2015a). Soil quality such as microbial efficiency and mineralized nitrogen content in the soil did not differ between organic and biodynamic treatments (Reeve et al. 2005, Döring et al. 2015, Meißner 2015) (Table 3).

Increased soil compaction under organic viticulture was reported in a long-term trial in Southern France (Coll et al. 2011). This might be due to a higher frequency of plant protection applications under organic farming.

Copper products are among the oldest plant protection agents and represent an important part of the plant protection strategy against downy mildew (caused by *Plasmopara viticola*) in organic viticulture. However, Cu is accumulated in the soil and high Cu content in vineyard soils is mainly due to anthropogenic inputs in past decades (Probst et al. 2008, Strumpf et al. 2009). Primarily Cu inputs from 1890 to 1940 were up to 50 kg/ha/year in viticulture (Strumpf et al. 2011). In long established winegrowing regions with long-term Cu application, Cu levels in the soil are higher compared to areas where viticulture was developed within the last three to five decades (Strumpf et al. 2009). There is no direct correlation between Cu content in the soil and its plant availability (Steindl et al. 2011). Copper content in grapes is low even if Cu content in the soil is high (Strumpf et al. 2009). Copper levels in viticultural soils have impact on total carbon, enzyme activities and biodiversity, especially on earthworm abundance in the soil (Paoletti et al. 1998, Mackie et al. 2013). Although amounts of Cu used for plant protection in organic viticulture are higher compared to the amounts usually used in conventional viticulture, organically managed vineyard soils in France, Croatia and Germany did not have a higher Cu content compared to their conventional counterparts (Probst et al. 2008, Coll et al. 2011, Strumpf

et al. 2011, Radić et al. 2014). Beni and Rossi (2009), in contrast, observed higher total Cu contents under organic farming after nine years in Italy. In an Italian study on organic viticulture Cu amounts in soils, on berries and in wines were below the maximum residue levels (Provenzano et al. 2010). Since vineyard soils under conventional, organic or biodynamic management did not show differences in Cu levels in most of the studies, there were no negative implications for earthworms in the soil (Strumpf et al. 2011).

Management Effects on Biodiversity

Biodiversity in agroecosystems provides multiple ecological services beyond food production that leads to increasing internal regulation of the latter (Altieri 1999). Results concerning biodiversity in annual crops and grasslands support the hypothesis that organic farming enhances biodiversity. There is evidence that organic agricultural methods increase species richness and abundance compared to conventional farming systems (Bengtsson et al. 2005, Hole et al. 2005). On average, species richness was 30 % higher and organisms were 50 % more abundant in organic farming systems compared to conventional management in annual crops (Bengtsson et al. 2005). Still, effects differed between organism groups and landscapes and benefits for biodiversity have not always been found. Birds, predatory insects, soil organisms and plants showed enhanced biodiversity under organic farming, while nonpredatory insects and pests did not (Bengtsson et al. 2005, Hole et al. 2005). It is controversially discussed whether an organic whole-farm approach provides more benefits for biodiversity than the establishment of small habitats within intensively used agricultural land (Hole et al. 2005). Further research is needed to assess the long-term effects of organic agriculture on biodiversity. Perennial cropping systems such as vineyards could be a good model for long-term studies on biodiversity since their lifespan usually comprises at least a few decades and they often provide habitats for rare and endangered species because of their climatic peculiarities (Bruggisser et al. 2010). Thus biodiversity in perennial systems such as vineyards can generally be very high (Isaia et al. 2006, Peverieri et al. 2009). Nevertheless, the effects of organic management on biodiversity in perennial crops have not been reviewed.

One hypothesis claims biodiversity under organic management in perennial crops to decline compared to conventional management. According to the intermediate disturbance hypothesis (Grime 1973, Horn 1975, Connell 1978, Bruggisser et al. 2010) biodiversity is linked to the level of disturbance in agro-ecosystems (caused by agricultural practices such as ploughing or mulching) in a non-linear way. At intermediate disturbance levels the highest biodiversity is found. Perennial cropping systems are characterized by a lower level of background disturbance in relation to annual cropping systems. It is hypothesized that in perennial cropping systems a further increase in disturbance, as caused by organic management, leads to a decline of biodiversity in contrast to annual cropping systems, where an increase of the level of background disturbance leads to an increase in biodiversity (Bruggisser et al. 2010).

Microbial Diversity in the Vineyard

Abundance of arbuscular mycorrhizal fungi increased under organic management (Freitas et al. 2011, Radić et al. 2014). Fungal endophyte colonization of the roots of grapevines and associated weeds under organic management, species richness, diversity indices and arbuscular mycorrhizal spore abundance were higher compared to conventional management (Radić et al. 2014). No difference in fungal species richness was assessed in soils of biodynamically and conventionally managed vineyards in New Zealand (Morrison-Whittle et al. 2017). In contrast, management systems differed in the types of species present and in the abundance of the single species. These results are supported by Hendgen et al.(2018), who recently observed a fungal community shift under organic viticulture in the topsoil layer without affecting fungal species richness in a long-term field trial in Germany. Bacterial biodiversity was increased in topsoil under organic management compared to conventional viticulture, the latter using mineral fertilizers, herbicides and synthetic fungicides (Hendgen et al. 2018).

Several different vineyards in different locations differing in the management approaches (organic or integrated) were compared concerning fungal endophytic communities on grapevine stems using both cultivation-based and cultivation-independent methods. The fungal endophytic communities under organic management were different from the ones under integrated management (Pancher et al. 2012). Fungicides used in the respective management approaches

may be the driving force in shaping fungal community composition. The level of tolerance of the fungi to the applied fungicides is unknown. The application of organic fertilizers in organic viticulture might be another factor that potentially influences fungal community composition. Variability of fungal endophytic communities from farms applying integrated pest management is described as smaller compared to organic farms. *Aureobasidium pullulans* was ubiquitous on farms with integrated pest management (Pancher et al. 2012). Schmid et al. (2011), in contrast, found *Aureobasidium pullulans* to be characteristic for organically managed vineyards. In this latter study organically and conventionally managed vineyards were compared concerning epiphytic and endophytic microbial communities on leaves, shoots and grapes close to harvest in two subsequent years. Molecular analysis was performed by DNA extraction and fingerprinting. The conventional treatment showed highest abundance of *Sporidiobolus pararoseus*, whereas the organic treatment showed highest abundance of *Aureobasidium pullulans*, as mentioned above. Authors explain its presence in organic viticulture with its properties to metabolize inorganic sulfur and absorb Cu. On the other hand it remains unclear why Pancher et al. (2012) found it to be characteristic for integrated pest management. Fungal ITS copy number was higher in organic compared to conventional treatment samples indicating a higher fungal diversity in organic viticulture. Antiphytopathogenic potential of fungal isolates is described as higher for organic management. No differences concerning bacterial community composition were described (Schmid et al. 2011). The composition of the epiphytic microbial community on ripening Riesling grapes was not different among management systems in a field trial comprising integrated, organic and biodynamic management (Kecskeméti et al. 2016). Fungal species richness in bark and on ripe fruit assessed by metagenomics was higher in biodynamic compared to conventional viticulture (Morrison-Whittle et al. 2017). In bark, species richness differed but not types or abundance. Species richness describes the number of species present in a certain environment, while abundance describes the number of single individuals of the same species present in the latter. While species richness and species abundance might be the same in two different environments, the types of species can potentially differ from one environment to the other. On ripe fruit, types of species and abundance differed between management systems. Differences in abundance of the genera *Columnosphaeria*, *Davidiella*, *Hanseniaspora*, *Chalara*,

and *Trichothecium* were detected. The observed differences in fungal biodiversity and abundance did not lead to a different community composition in the harvested juice (Sauvignon blanc) of biodynamically and conventionally managed vineyards. This might be due to a rough change of the environmental conditions from grape berries to pressed juice. Many yeasts that are present on harvested grapes are not adapted to the environment with low pH, lack of oxygen and high sugar contents as it occurs in grape juice (Morrison-Whittle et al. 2017). Bagheri et al. (2015) assessed yeast population dynamics during spontaneous fermentation in Cabernet Sauvignon musts from biodynamic, integrated and conventional management in South Africa. The farming systems differed in yeast community composition. The biodynamic vineyard had the highest culturable yeast diversity in both years of the study and the highest initial number of culture forming units (CFU) indicating a higher species abundance. *Candida parapsilosis* and *Saccharomyces cerevisiae* were exclusively isolated from biodynamic musts at the start of fermentation. Cultivation-based assessment of the yeast community by Fourier-transform infrared spectroscopy (FTIR), in contrast, showed a lower abundance of yeasts under biodynamic in contrast to conventional management (Guzzon et al. 2016). These different results concerning yeast abundance under biodynamic and conventional viticulture might be due to isolation and cultivation techniques on one hand and due to different environmental conditions and management on the other hand.

There is evidence that diversity of the microbial community on grapes and vines is enhanced under organic viticulture, although no characteristic fungi or bacteria for organic management could be found. Different results concerning the microbial community composition in one vineyard over the years indicate that the community composition is highly dependent on climatic conditions of every single vintage (Bagheri et al. 2015, Guzzon et al. 2016). Results concerning single yeast strains, fungi or bacteria seem to be either influenced by climatic conditions, sampling date, specific pest management strategies or isolation techniques. On the other hand the plant protection strategy is likely to highly influences yeast and fungal community composition, since most of the agents used in organic and in conventional viticulture are fungicides against downy and powdery mildew. Little is known about their impact on the different yeast strains and fungi on grapes and vines.

Floral Biodiversity

Bruggisser et al. (2010) investigated biodiversity in organic and conventional Swiss vineyards at different trophic levels. Neither plant diversity, abundance, or richness was enhanced under organic viticulture compared to conventionally managed vineyards, and no species were found that exclusively occurred in organically managed sites. Nascimbene et al. (2012) detected higher plant species richness in organically managed vineyards and adjacent non-crop areas compared to conventional management within an intensively used agricultural landscape in northern Italy. The positive effect of organic viticulture on local plant species richness could be due to the intensively farmed and homogeneous landscape in northern Italy compared to Switzerland meaning that the landscape context might modify the beneficial effects of organic viticulture on biodiversity (Brittain et al. 2010, Nascimbene et al. 2012). The use of herbicides in conventional viticulture might account for the observed differences, while mechanical operations and mowing regime did not differ between management systems (Nascimbene et al. 2012). In both vineyards and grassland strips organic viticulture promoted growth of perennial species (higher abundance) in contrast to conventional farming indicating a negative impact of herbicide application on the establishment of perennial plant species (Nascimbene et al. 2012). A recent study conducted in northern Spain comparing conventionally and organically managed vineyards found organic plots to host a richer community of vascular plants (Puig-Montserrat et al. 2017). Vegetation species density was higher under organic farming. As in the previous study the use of herbicides might account for the lower community richness under conventional viticulture (Puig-Montserrat et al. 2017).

Earthworm Biodiversity

Earthworm abundance increased under organic and biodynamic management compared to integrated viticulture (Collins et al. 2015b, Meißner 2015) and was even higher under biodynamic compared to organic viticulture in a replicated field trial in Germany (Meißner 2015). It is likely that the stimulation of the biological activity of the soil under organic and biodynamic management is due to the use of cover crop mixtures with a wide range of species which enhances earthworm biodiversity and abundance. This effect was confirmed in different agroecosystems (Mäder et al. 2002, Blanchart et al. 2006). In contrast Coll et al. (2011) found

endogeic earthworm density and biomass to decrease under organic viticulture. This result might suggest a shift in the earthworm community under organic management. In the same study increased plant- and fungal-feeding nematode densities under organic management as well as a decreased ratio of bacterial-feeders/fungal feeders characteristic for organic farming were observed (Coll et al. 2011).

Acarian Biodiversity

Populations of the predatory mite *Typhlodromus pyri*, a useful creature in vineyards for spider mite control (Duso 1989), have been shown to decrease under organic management because of the higher frequency of sulfur sprays compared to conventional viticulture (Linder et al. 2006, Fleury and Fleury 2016). A study done in Australia, however, found abundance of predatory mites to be higher compared to conventionally managed blocks (Wheeler 2006). This could be due to a lower spraying frequency in Australian drier conditions or due to the use of insecticides in the conventional plots. A comprehensive study in different Italian winegrowing regions that focused on predatory mite populations (Phytoseiidae and Tydeidae) in untreated, organic and conventional vineyards found biodiversity in untreated and organic vineyards to be higher compared to conventional ones (Peverieri et al. 2009). Mite populations of untreated and organic vineyards were more similar to each other than conventional ones. This finding supports the hypothesis that arthropod biodiversity is increased under organic farming. Some predatory mite species were exclusively recorded in untreated and organic vineyards (*K. aberrans* and *T. pyri*).

Biodiversity of Insects and Spiders in the Vineyard

Species richness of butterflies was enhanced under organic viticulture in northern Spain (Puig-Montserrat et al. 2017). The same authors investigated moth community composition in organic and conventional vineyards, but results were less significant. Conventional vineyard management is characterized by the use of wide-spectrum insecticides. Their use might affect the lepidopteran community and might therefore account for the loss of butterfly species richness under conventional viticulture. Larvae of moths are also susceptible to wide-spectrum insecticides. It remains unclear why the moth population was less affected in the latter study. Organic viticulture did not promote diversity or abundance of grasshoppers in a swiss study

(Bruggisser et al. 2010). Grasshopper diversity was even lower under organic compared to conventional viticulture. Grasshopper diversity was in contrast enhanced by mulching compared to mowing, which displays a lower disturbance level. Authors conclude that the background disturbance level under organic viticulture in this case was too low to be beneficial for biodiversity of grasshoppers (Bruggisser et al. 2010).

Brittain et al. (2010) investigated whether isolated organic farms provided benefits for insect pollinators and pollination services in an intensively farmed landscape in Northeast Italy. According to Brittain et al. (2010) organic and conventional vineyards did not differ in their floral resources or proportion of surrounding uncultivated land. Neither pollinator abundance nor species richness, visitation rates of pollinators or pollination of experimental potted plants were affected by the management system. Vegetation control within rows did not differ between the two farming systems in this study and was done by mowing. Taking into account these two characteristics of the study it is not surprising that no differences in pollinator population or pollination services were found.

When biodiversity of arthropods was compared the organic and the biodynamic treatment showed higher numbers of arthropods in the canopy and in the green cover as well as an increased biodiversity of the latter (Meißner 2015). Fleury and Fleury (2016) monitored ladybird populations in organically and conventionally managed vineyards in Switzerland and observed a higher abundance, but a lower biodiversity of ladybirds under organic management. Abundance of detritivores and colembola was assessed in two Australian studies and shown to be higher under both organic and biodynamic management (Wheeler 2006, Collins et al. 2015b). Organic viticulture increased arthropod predator biodiversity and abundance in a study conducted in Northwest Italy (Caprio et al. 2015). Still different species responded differently to the different farming systems. Some carabids and spiders preferred organic and some others preferred conventional vineyards. Preference patterns of spiders in general were shown not only to be driven by the farming system itself, but also by habitat features such as grass cover and small-scale landscape structures such as bushes, trees and small forest patches. Overall biodiversity and abundance of spiders such as arthropod predators were higher in organic vineyards and even in forest patches adjacent to organic vineyards which were typically located below the sampled

vineyards. Therefore a leaching effect of chemicals and fertilizers could explain the enhanced biodiversity in organically managed sites, since no synthetic insecticides are allowed in organic viticulture (Caprio et al. 2015). Another study on spider community composition under organic and conventional viticulture in Northwest Italy confirmed the diversity of spider species to be higher in certified organic vineyards. The level of dominance of spider species was lower for certified organic in contrast to conventional vineyards. A low level of dominance is one important parameter for indicating biodiversity together with high species richness and high species abundance (Isaia et al. 2006). Landscape heterogeneity seems to be as important to maintain high diversification of spider hunting strategies, which may improve natural pest control (Isaia et al. 2006, Caprio et al. 2015). In the swiss study assessing biodiversity of plants, grasshoppers, and spiders no difference in spider abundance or diversity was detected between organic and conventional vineyards (Bruggisser et al. 2010). As shown previously, landscape features play a major role in determining diversity of spiders (Isaia et al. 2006, Caprio et al. 2015). In the case of the location of Ligerz in northern Switzerland the diversity of landscape patterns and the proximity of a nature conservation area might modify the benefits of organic viticulture assessed in other studies (Brittain et al. 2010, Nascimbene et al. 2012).

Biodiversity of Birds in the Vineyard

Birds showed no significant response to treatments comparing organic and conventional vineyards in northern Spain (Puig-Montserrat et al. 2017) nor in northeast Italy (Assandri et al. 2016). Maintaining patches of residual habitats in the vineyard and enhancing landscape heterogeneity are two key factors to enhance biodiversity of avian communities in vineyards in an intensively used agricultural landscape (Assandri et al. 2016). Mobile taxa such as birds may be less influenced by the management system of one specific vineyard (Puig-Montserrat et al. 2017). Nonetheless Caprio and Rolando (2017) detected positive effects on the feeding ecology of great tits (*Parus major*) under organic viticulture in northwestern Italy. Landscape variables did not differ between organic and conventional vineyards. Differences in the number of nestlings fed per visit and the weight of the nestlings suggest that organic vineyards offer more

feeding resources. The diet of nestlings was unaffected by the management system (Caprio and Rolando 2017).

Pest management strategies, application of herbicides as well as the diversity of cover crops and the use of compost seem to mainly influence biodiversity in the biosphere of vineyards. Plant species richness seemed to be higher under organic management mostly due to the absence of herbicide application. Results were dependent on the landscape context which might modify the beneficial effects of organic viticulture on biodiversity. Results concerning the earthworm population in different trials indicate an increase in abundance under organic and biodynamic viticulture as well as a community shift. Cover crop mixtures rich in species used in organic and biodynamic in contrast to conventional viticulture could be responsible for the described phenomena. Results concerning predatory mite populations in vineyards are mixed and might be very dependent on the frequency of sulfur sprays under organic viticulture. A comprehensive study from Italy showed untreated and organic plots to have a higher biodiversity of predatory mites compared to the conventional treatment. Results concerning the biodiversity of different insect species are mixed. In general abundance and diversity of insects under organic viticulture either increased or did not differ from conventional viticulture. Results seemed to be highly dependent on the implementation of cover cropping in the organic treatment and on the landscape context. If investigated organic and conventional treatments did not differ in their flowering resources, it was unlikely that differences in insect biodiversity occurred. Some studies showed that fungicide and herbicide application in conventional viticulture had negative effects on insect biodiversity or abundance. Several studies showed the influence of landscape-induced background biodiversity in the region on biodiversity levels within the different management systems in vineyards. In intensively farmed and homogeneous landscapes the enhanced biodiversity under organic viticulture was more evident meaning that the landscape context might modify the beneficial effects of organic viticulture on biodiversity. The effect of the farming system seems to be more pronounced on less mobile taxa (Puig-Montserrat et al. 2017). Birds, for example, were little influenced by the management system.

The intermediate disturbance hypothesis that predicted a loss of biodiversity in organically grown perennial crops due to the lower background disturbance level of organic

farming must be rejected. Biodiversity in most trophic levels was enhanced under organic viticulture. 17 out of 24 studies showed a clear increase in biodiversity under organic viticulture. The impact of a decrease in disturbance does not only depend on the general level of disturbance, but also on the taxon investigated and the type of disturbance measured. The diversity maxima of different taxa may not be at the same position along the disturbance gradient. This is why the impact of a certain disturbance level on one taxon cannot necessarily be used to predict the impact on other taxa. Therefore the intermediate disturbance hypothesis is only applicable for one single taxon, but not for a whole community of interacting taxa (Bruggisser et al. 2010). Organism-, site- and crop-specific management strategies to enhance biodiversity in perennial crops should be developed. The conservation of specific taxa or organisms within an agricultural system is of high importance, because a general decrease in biodiversity within an agricultural system may lead to functional shifts when sets of species are replaced by others with different traits due to anthropogenic disturbance (Bruggisser et al. 2010).

Management Effects on Vine Growth

A reduction in vigor, expressed as pruning weight, shoot length, canopy density or leaf area index (LAI), respectively, of organically managed vineyards compared to conventional management was observed for several white varieties such as Riesling, Kerner and Müller-Thurgau (Hofmann 1991, Corvers 1994, Kauer 1994, Döring et al. 2015, Meißner 2015) and for the red varieties Grignolino and Cabernet Sauvignon (Malusà et al. 2004, Pike 2014, Collins et al. 2015b) (Table 2). However, LAI did not differ among treatments according to Corvers (1994) (Riesling and Kerner). When pruning weight of organic and conventional management was compared by meta-regression analysis taking into consideration all available datasets of scientific trials, organic and biodynamic treatments showed 21 % less growth as pruning weight compared to conventional treatments (Fig 1).

Pruning weight of organic and biodynamic treatments differed from conventional/integrated treatments in the respective field trials. The environmental factors had a significant influence on the pruning weight, but no interactions between treatment and environment were observed, meaning that organic and biodynamic treatments always showed

lower pruning weights regardless of the location of the trial (S2 Table). All the studies included showed an average reduction in pruning weight under organic management (S1 Fig).

The relative vegetative growth expressed as pruning weight under organic in comparison to conventional viticulture ranged between 57.1 % and 104 %. No clear relationship between the level of conventional pruning weights and relative organic pruning weights could be observed taking into account the data of field experiments available (Fig. 2).

Chlorophyll content in leaves at veraison and macronutrient supply in leaves at veraison did not show differences among treatments (Linder et al. 2006, Döring et al. 2015, Meißner 2015). Danner (1985) reported a reduction of the nutrient supply for organic production in a field trial comparing organic, biodynamic and conventional viticulture from 1979 to 1983 in Mailberg, Austria (Grüner Veltliner). Nitrogen content in leaves was lower under organic and biodynamic management (Danner 1985, Malusà et al. 2004). Döring et al. (2015) showed nitrogen content in leaves at veraison under organic and biodynamic management to be higher in comparison to integrated management. At the same time mineralized nitrogen content in the soil of the respective treatments was higher, as mentioned above. In the same trial chlorophyll content was shown to decrease at veraison under organic and biodynamic management (Döring et al. 2015, Meißner 2015). Magnesium and phosphorus content in leaves decreased under organic and biodynamic production systems compared to conventional systems in Germany as well as in Australia (Collins et al. 2015b, Döring et al. 2015) (Table 2).

Macronutrient supply and content in leaves seems to be highly influenced by the management within organic, biodynamic or conventional treatments. It was shown that it is possible to ensure nitrogen and macronutrient supply without the use of synthetic nitrogen fertilizers, although nitrogen content in the soil and in the leaves is highly dependent on fertilization strategy and water availability. It is notable that phosphorus content in the Australian as well as in the German long-term field trial were lower under biodynamic and in Australia also under organic management. This could be due to the lower water availability in the respective systems measured as soil moisture or pre-dawn water potential Ψ_{pd} , respectively (Collins et al. 2015b, Döring et al. 2015). Magnesium content in leaves or petioles was also shown to be lower under organic and biodynamic management in both trials and might account for the decrease in

chlorophyll content at veraison monitored in the organic and the biodynamic plots in the long-term trial in Germany.

Physiological performance was reported to decrease under organic and biodynamic management (Döring et al. 2015). In case of the biodynamic production system pre-dawn water potentials Ψ_{pd} also decreased in comparison to the conventional production system in Germany, whereas no differences in stem water potential among systems could be detected close to harvest in Australia (Döring et al. 2015) (Collins and Döring unpublished) (Table 2).

Growth and vigor expressed as pruning weight, shoot length, canopy density or LAI decreased under organic and biodynamic in comparison to conventional viticulture. Since in organic plots microbial soil activity and soil organic carbon were generally higher and no consistent difference in soil N, P, S could be observed in several field trials, these parameters cannot account for the observed differences in growth. The only study that reports a reduction in nutrient supply under organic production was performed in Austria at the beginning of the 1980's. It seems more likely that the observed reduction in physiological performance in organic plots reported by Döring et al. (2015) might account for the growth differences between conventional and organic management. Authors observed changes in physiological performance under organic and biodynamic management after full-bloom especially under dry conditions in Germany. At the same time pre-dawn water potentials decreased under organic and biodynamic management. It could be hypothesized that the cover crop mixture rich in legumes used in organic and biodynamic viticulture to enhance biodiversity and to ensure nitrogen supply have an impact on water availability in the soil and thus compete with the root system of the vines. Under dry conditions with irrigation in Australia no differences in stem water potential among treatments could be observed before harvest (Collins and Döring unpublished), although growth and canopy density in the organic and biodynamic plots decreased in the trial. This could be due to the fact that natural vegetation between rows occurs in the organic and the biodynamic system in spring when soil water availability is higher. During the dry growing season the natural vegetation senesces, but it could still influence root growth in the respective management systems. When soil moisture was assessed in the long-term field trial in Australia during the growing season 2010/2011, a significant decrease of soil moisture content under organic

management at 20 cm up to 1 m depth was observed compared to the high input conventional system (Collins et al. 2015b). It is likely that differences in the root system of the vines or the water availability in the soil due to cover cropping might account for different levels of plant growth regulators such as abscisic acid and cytokinin that strongly determine growth and vigor (Stoll et al. 2000).

When comparing yield/pruning weight ratios of organic and biodynamic viticulture they were found to be significantly lower in biodynamic viticulture (Merlot) (Reeve et al. 2005) (Table 3). This difference was due to a slightly higher yield in the organic treatment, while pruning weights itself did not differ between treatments. However, other studies did not assess differences in the yield/pruning weight ratios between organic and biodynamic plots (Collins et al. 2015b, Döring et al. 2015). No differences between organic and biodynamic treatments were observed concerning pruning weight, LAI and leaf area/fruit weight-ratio (Döring et al. 2015, Meißner 2015). Results by Reeve et al. (2005) and Collins (unpublished) partially showed higher pruning weight for biodynamic compared to organic management, but the other studies showed ratios of pruning weight under organic and biodynamic management to be similar.

Macronutrients as well as chlorophyll content in leaves did not differ between organic and biodynamic plots for Riesling (Döring et al. 2015, Meißner 2015) (Table 3). Since all nutrients are transported within the plant in the xylem and xylem sap flow can only be ensured if there is enough plant available soil water, nutrient supply and water uptake are closely related (Yang and Tyree 1992). Two recent studies on organic and biodynamic viticulture observed significantly lower pre-dawn water potentials in the biodynamic plots, cv. Riesling in Germany (Döring et al. 2015) and cv. Sangiovese in Italy (Botelho et al. 2015). The relation of pre-dawn or soil water potential and stomatal conductance of plants is usually plant- and environment-specific, but nonetheless very close (Tramontini et al. 2014). One of the two studies that observed differences in pre-dawn water potential between organic and biodynamic viticulture observed stomatal conductance of the biodynamic plots to be lower (Botelho et al. 2015), whereas in the other study the lower water potential did not have implications on the physiological performance of the plants (Döring et al. 2015). In the Italian field trial where lower stomatal conductance under biodynamic viticulture occurred, a significant increase in leaf

enzymatic activity (endochitinase, β -N-acetylhexoaminidase, chitin 1,4- β -chitobiosidase, β -1,3-glucanase) of the biodynamic plots for Sangiovese was observed (Botelho et al. 2015). The enzymatic activities that were found to increase under biodynamic management are linked to biotic and abiotic stress and are associated to induced resistance against several fungi such as powdery mildew (*Erysiphe necator*), downy mildew (*Plasmopara viticola*) and Botrytis bunch rot (*Botrytis cinerea*) (Giannakis et al. 1998, Reuveni et al. 2001, Magnin-Robert et al. 2007). One hypothesis is that especially the biodynamic horn silica preparation 501 (Table 1) made from quartz powder and used in very small quantities might upregulate plant defense mechanisms attributed to induced plant resistance (Botelho et al. 2015). However, the plots of the study by Botelho et al. (2015) were replicated, but not randomized. This is why the observed changes in physiological performance and enzymatic activity cannot clearly be attributed to the treatment and need to be confirmed.

Management Effects on Yield

A meta-analysis on annual and perennial crops under organic and conventional management reveals organic yields of individual crops to be on average 80 % of conventional yields (De Ponti et al. 2012). This organic yield gap, though, may differ among crops and regions. It is hypothesized that the yield gap between organic and conventional production is higher than 20 % at high yield levels and lower than 20 % at low yield levels (De Ponti et al. 2012). It is hypothesized that the increasing yield gap with higher conventional yield levels may be due to yield losses by pests and diseases and/or lower P availability under organic farming. The average relative yield for fruits in this latter study was 72 % including grapes, melons, apricot, blackcurrant, cherry, peach, pear and others (De Ponti et al. 2012). Another meta-analysis found yields of organically grown annual crops and animal products such as milk to be 91 % of the conventional yields (Stanhill 1990).

A yield loss from 10 % up to 30 % is reported for organic viticulture compared to conventional production for several white varieties such as Riesling, Kerner, Müller-Thurgau, Grüner Veltliner, Chardonnay, Seyval and for red varieties Grignolino, Cabernet Sauvignon, Merlot, Shiraz and Concord (Danner 1985, Hofmann 1991, Corvers 1994, Kauer 1994, Pool and

Robinson 1995, Malusà et al. 2004, Wheeler 2006, Collins et al. 2015a, Döring et al. 2015, Meißner 2015) (Table 2). Meta-Regression analysis shows that organic and biodynamic treatments have in average 18% less yield compared to conventional treatments (Fig 3). The average yield gap observed in viticulture is similar to that in annual crops.

Yield of organic and biodynamic treatments differed from conventional/integrated treatments in the respective field trials. The environmental factors had a significant influence on the yield levels, but no interactions between treatment and environment were observed, meaning that organic and biodynamic treatments always showed significantly lower yields regardless of the location of the trial (S2 Table). All the studies included in the meta-analysis and the meta-regression showed lower average yields for organic or biodynamic compared to conventional management (S2 Fig).

The yield gap under organic compared to conventional viticulture ranges from 44.2 % to 119.4 % for the data included into the meta-analysis. Looking at the relative organic yield in proportion to the yield level of the conventional or integrated counterpart, no clear relationship between conventional yield level and relative organic yield can be observed (Fig. 4), meaning that organic relative yields do not automatically decrease when yield levels increase in conventional viticulture.

In the case of Chasselas in Perroy (Waadt, Switzerland) (Linder et al. 2006), Riesling in Geisenheim (Rheingau, Germany) (Döring et al. 2015, Meißner 2015) and Elvira in Geneva (New York State, US) (Pool and Robinson 1995), a reduction of the berry weight under organic and biodynamic production was observed. Yet Corvers (1994) and Pool and Robinson (1995) reported that single berry weight did not differ among treatments from 1990-92 in Erbach and Hattenheim (Rheingau, Germany) (Riesling and Kerner) and from 1990-94 in Geneva (New York State, US) (Concord and Seyval), respectively (Table 2).

Organic and biodynamic plots showed lower compactness of bunches (Riesling) (Döring et al. 2015, Meißner 2015). The number of berries per bunch and the average bunch weight was significantly lower under organic and biodynamic management (Corvers 1994, Döring et al. 2015), whereas Pool and Robinson (1995) did not report a difference in the number of berries per bunch and the average bunch weight between management systems (Table 2). The reduced berry

weights, reduced bunch weights and reduced number of berries per bunch, that were observed under organic and biodynamic management in many trials, could be due to a different water availability in the soil (Collins et al. 2015b) and a reduced physiological performance around full-bloom (Döring et al. 2015) and could be one reason for the yield decrease described above. Fruit set was not assessed in any of the trials, but fruit set is likely to differ between treatments, because they were shown to differ in growth, water availability in the soil and physiological performance at full-bloom.

Döring et al. (2015) provide evidence that the vine water status and thus the physiological performance differs between organic or biodynamic and conventional viticulture. Since reproductive development of *Vitis vinifera* is highly sensitive to the water and nitrogen status the lower water availability in the organic and the biodynamic management system might account for the differences in physiological performance and might cause yield differences. Lower water availability early in the season was shown to cause decreases in yield and cluster weight (Matthews and Anderson 1989). Since the period from initiation to maturation of winegrapes comprises two growing seasons, early season water deficit might have implications for cluster weight of the current year and the number of clusters of the subsequent year (Matthews and Anderson 1989, Döring et al. 2015). There is evidence that water availability in hot as well as in cool climate viticulture plays a key role in determining vigor and yield under organic and biodynamic viticulture. How P and Mg availability is influenced by the different water availability in the differing viticultural management systems should be a subject of further research. It is still unclear to which extend the lower P and Mg availability under organic and biodynamic viticulture determines growth and yield of the respective systems.

No yield differences were observed between organic and biodynamic treatments for Merlot, Sangiovese, Cabernet Sauvignon and Riesling (Reeve et al. 2005, Botelho et al. 2015, Collins et al. 2015a, Döring et al. 2015, Meißner 2015) (Table 3). Danner (1985) detected lower yields for the biodynamic plots in respect to the organic plots in two out of five years of the study done in Austria on Grüner Veltliner. The organic and the biodynamic treatment did not differ in the number of bunches per vine, in the cluster weight, the cluster compactness and the berry weight (Reeve et al. 2005, Döring et al. 2015, Meißner 2015).

Management Effects on Disease Incidence

Disease incidence of downy mildew (*Plasmopara viticola*) did not show any differences comparing organic, biodynamic and conventional production for Grüner Veltliner in Austria under higher disease pressure and for Cabernet Sauvignon in Australia under low disease pressure (Danner 1985, Pike 2014). For Riesling under more humid climatic conditions, the incidence of downy mildew was significantly higher under organic and biodynamic production when the disease occurred (Döring et al. 2015) (Table 2). For Chasselas in Switzerland, the organic treatment showed significantly higher disease incidence of powdery mildew (*Erysiphe necator*) (Linder et al. 2006). Results are mixed concerning the disease incidence of Botrytis bunch rot (*Botrytis cinerea*). Danner (1985) reports that the organic treatment showed a higher disease incidence of Botrytis bunch rot compared to the biodynamic and the conventional treatment in three out of five years, whereas the biodynamic treatment showed a higher disease incidence of Botrytis bunch rot in just one out of five years compared to the conventional system. For Riesling the organic and the biodynamic plots showed lower disease incidence of Botrytis bunch rot compared to the integrated plot from 2006 to 2009 (Meißner 2015). The field trial was managed and conducted in the same way after conversion. In the following years of the same field trial from 2010 to 2012 the biodynamic treatment showed significantly higher disease incidence of Botrytis bunch rot compared to the integrated management system, whereas the organic treatment did not differ from the integrated plots (Döring et al. 2015) (Table 2). Under dry conditions in Australia the organic and the biodynamic plots did not differ from the conventional plots with respect to disease incidence of Botrytis (Pike 2014). This might be due to the low disease pressure under Australian conditions and Cabernet Sauvignon bunch architecture preventing infections of Botrytis bunch rot (Table 2). The organic and the biodynamic system showed significantly less sour rot on bunches in the field trial in Geisenheim (Rheingau, Germany) (Döring et al. 2015, Meißner 2015).

The direct comparison of biodynamic and organic viticulture revealed a higher disease incidence of Botrytis under organic management in three out of five years in the field trial in Austria (Danner 1985), but no difference was detected in the field trial in Germany (Döring et al.

2015) nor in Australia (Pike 2014) (Table 3). Organic and biodynamic viticulture did not differ in the disease incidence of downy mildew (Danner 1985, Pike 2014, Döring et al. 2015).

Disease incidence seems to be highly dependent on the grapevine variety, the location with its microclimate, the vineyard management and on the environmental conditions of every single year. Still it is not surprising that disease incidence of some grapevine diseases such as powdery and downy mildew is higher under organic or biodynamic management compared to conventional viticulture, since the organic and the biodynamic systems exclusively rely on fungicides such as Cu and sulfur and in addition plant resistance improvers. All these agents are strictly protectants and they do not act curatively, as some synthetic fungicides do. Besides that, no botryticides are applied in organic or biodynamic viticulture. Döring et al. quantified the potential yield loss in organic and biodynamic viticulture due to downy mildew over a three-year-period and concluded that only up to 10 % of the observed yield reduction in organic and biodynamic management could be attributed to the infestation with downy mildew in the year with the severest attack of downy mildew (Döring et al. 2015). This clearly underlines that other mechanisms must play a key role in causing the yield gap between organic and conventional production.

Management Effects on Fruit, Juice Composition, and Wine Quality

The impact of organic viticulture on grape quality parameters, juice and wine quality is inconclusive (Table 2). In a number of trials no consistent differences in grape composition of several researched grape varieties were observed (Danner 1985, Hofmann 1991, Kauer 1994, Henick-Kling 1995, Malusà et al. 2004, Linder et al. 2006, Tassoni et al. 2013, 2014, Collins et al. 2015a, Collins et al. 2015b, Döring et al. 2015), whereas Hofmann (1991) reported differences in winegrape quality between organic and conventional production depending on plant protection strategy and incidence of Botrytis at harvest. Coffey (2010) detected higher levels of zinc and iron in berries from organic management (Cabernet Sauvignon) in Australia. Corvers (1994) and Meißner (2015) observed that the integrated treatment showed significantly higher must acidity for the varieties Riesling and Kerner, respectively, in Germany, whereas in a study in Italy organic Sangiovese wines had higher malic acid and volatile acidity (Beni and

Rossi 2009). Tobolková et al. (2014) detected higher citric acid in wines from conventional management in Slovakian white wines. No differences in juice and wine quality were observed including acidity, macronutrients, and phenolic compounds (Danner 1985, Kauer 1994, Henick-Kling 1995, Dupin et al. 2000, Granato et al. 2015b, Granato et al. 2015c, Meißner 2015, Granato et al. 2016) (Table 2). Fritz et al. (2017) assessed juice quality in the first year of conversion according to image forming methods (biocrystallization, capillary dynamolysis and circular chromatography image analysis (Huber et al. 2010, Zalecka et al. 2010)) and ranked grape juices from organic and biodynamic plots better than grape juices from integrated plots due to their strength of form expression and their resistance to deterioration (Riesling). Cozzolino et al. (2009) correctly classified 85 % of their samples of Australian organic and non-organic wines according to mid infrared spectra by discriminant partial least squares. Meta-regression analysis shows that the juice sugar concentration of organically and biodynamically managed vineyards showed almost the same levels compared to that of conventionally managed vineyards (Fig 5).

Total soluble solids in juice of organic and biodynamic treatments did not differ from conventional/integrated treatments in the respective field trials. The geographic location of the trials had a significant influence on levels of total soluble solids, but no interactions between treatment and environment were observed, meaning that organic and biodynamic treatments never differed from conventional treatments in total soluble solids in juice regardless of the location (S2 Table). All the studies included in the meta-analysis and meta-regression showed similar amounts of total soluble solids for organic and conventional management (S3 Fig).

It was shown that growth as well as yield of grapevines under organic and biodynamic management generally decreases. One very important parameter determining potential level of total soluble solids in grape juice is the leaf area/fruit weight-ratio (Kliewer and Dokoozlian 2005). Döring et al. (2015) measured this ratio under integrated, organic and biodynamic management. The organic and the biodynamic treatments showed slightly higher levels of leaf area/fruit weight-ratio, but there was no difference among treatments. One reason why organically and biodynamically managed vineyards do not differ from conventional vineyards in total soluble solids in juice could be the simultaneous decrease of growth and yield resulting in a similar ratio of leaf area to fruit weight. Results by Collins et al. (2015b) concerning the ratio of

yield:pruning weight support that there is no difference among the systems concerning the ratio of reproductive and vegetative growth. Another reason for the fact that systems did not differ in the amount of total soluble solids at harvest might be that physiological performance (assimilation rate, transpiration rate and stomatal conductance) after veraison, that highly determines final sugar content and berry quality traits, did not differ among treatments when measured in the long-term field trial in Germany (Hardie and Considine 1976, Döring et al. 2015).

Yeast available nitrogen content (N-OPA) was shown to increase under biodynamic management after conversion (Döring et al. 2015), but N-OPA content did not differ among treatments in the first years of the same trial (Meißner 2015). The application of systemic fungicides in the integrated plot (Oliva et al. 2011) and the lower content of nitrogen in the soil of the integrated plots together with the high yields may have caused the decrease in N-OPA levels in berries of the integrated treatment (Döring et al. 2015).

Yildirim et al. (2007) found putrescine content to be significantly higher under organic viticulture, while Tassoni et al. (2013) did not detect differences in the content of biogenic amines in wines from different management systems.

There is evidence that anthocyanin and flavonoid content in berry skin as well as polyphenol content, antioxidant potential and phenolic acid content in juice and wine, resveratrol content and enzyme polyphenol oxidase concentration in grapes increase under organic management (Tintunen and Lehtonen 2001, Micelli et al. 2003, Malusà et al. 2004, Yıldırım et al. 2004, Núñez-Delicado et al. 2005, Otreba et al. 2006, Dani et al. 2007, Vrček et al. 2011, Rodrigues et al. 2012, Buchner et al. 2014, Granato et al. 2015a). Other studies did not observe any differences in the polyphenol or anthocyanin profiles of grapes and wines, their carotenoid and *trans*-resveratrol content, content of *p*-coumaric acid or their antioxidant activity (Lante et al. 2004, Mulero et al. 2009, 2010, Bunea et al. 2012, Tassoni et al. 2013, Collins et al. 2015a, Collins et al. 2015b, Garaguso and Nardini 2015). Total polyphenol content and antioxidant activity in wines even decreased under organic viticulture in some other studies (Yıldırım et al. 2004, Beni and Rossi 2009). Moreover, ascorbic acid equivalents, ferric-reducing power as well as Cu and Fe in wines were found to be reduced (Tobolková et al. 2014).

It is likely that the different treatments differ in polyphenol content, since the synthesis of these parameters is highly linked to light interception in the canopy. Organic and biodynamic treatments showed significantly lower growth, lower canopy density and lower secondary shoot growth. This lower vigor might induce higher levels of flavonoids, anthocyanins and thus a higher antioxidant potential (Cortell et al. 2005). On the other hand the organic and the biodynamic plots also had lower yields, which might result in no change in the polyphenol content. Fruit-zone leaf removal potentially has a strong effect on light interception and thus phenolic composition of the grapes. In the trials comparing the different management systems fruit-zone leaf removal was not implemented for not interfering too much with the systems performance.

Several studies focused on grape composition under organic and biodynamic viticulture including total soluble solids, acidity, macronutrients and phenolic compounds. Most of the studies revealed that there was no difference including varieties such as Grüner Veltliner, Merlot, Pignoletto, Sangiovese, Cabernet Sauvignon, Albana, Lambrusco, Riesling (Danner 1985, Reeve et al. 2005, Tassoni et al. 2013, Laghi et al. 2014, Tassoni et al. 2014, Collins et al. 2015b, Döring et al. 2015, Granato et al. 2015a, Granato et al. 2015c, Meißner 2015, Parpinello et al. 2015, Picone et al. 2016, Patrignani et al. 2017) (Table 3). Almost all the studies included in the meta-analysis and meta-regression showed similar levels of total soluble solids for organic and biodynamic viticulture.

Nonetheless some authors assessed differences in the chemical composition of berries, juices or wines grown organically and biodynamically (Table 3). Meißner (2015) detected a lower juice acidity in fruit managed biodynamically (Riesling). Fritz et al. (2017) assessed juice quality in the first year of conversion according to image forming methods (biocrystallization, capillary dynamolysis and circular chromatography image analysis (Huber et al. 2010, Zalecka et al. 2010)) and ranked grape juices from biodynamic plots better than grape juices from organic plots (Riesling). Some studies revealed that there was an increase in total phenols, total anthocyanins, γ -aminobutyric acid as well as amino acids and organic acids under biodynamic viticulture for Sangiovese and Merlot (Reeve et al. 2005, Laghi et al. 2014, Picone et al. 2016). Laghi et al. (2014), Parpinello et al. (2015) and Picone et al. (2016) detected a decrease in sugars,

alcohol content, phenolic compounds, wine color, total polymeric pigments and tannins as well as coumaric and *trans*-caffeic acid (cv. Sangiovese). One hypothesis could be that the lower stomatal conductance, as observed in biodynamically managed plants led to a higher concentration of internal CO₂ (Botelho et al. 2015, Picone et al. 2016). A higher internal CO₂ concentration could then lead to a predominance of the anaerobic metabolism in biodynamically grown berries compared to organically grown ones (Picone et al. 2016). It is thought that in berries of biodynamic management the fermentative pathway is activated (Picone et al. 2016). Lower sugar concentration, an increased concentration of organic acids such as lactate and malate in biodynamically grown berries might be one sign of the activation of the anaerobic metabolism (Picone et al. 2016), although further research is needed to confirm this hypothesis. Moreover, the field trial on Sangiovese has no randomized field replicates. This is why it is not clear whether the observed phenomena are an effect of the plot or of the treatment.

Results by Meißner (2015) suggest a lower juice acidity in biodynamically grown grapes which is contrary to a higher concentration of organic acids, as found by Picone et al. (2016). The increase of phenolic compounds under biodynamic management, as described by Reeve et al. (2005), could confirm the hypothesis of an upregulation of substances attributed to induced resistance in biodynamically grown plants, as expressed by Botelho et al. (2015). Still Parpinello et al. (2015) found total polymeric pigments as well as tannin concentration and total color under biodynamic management decreased in the first two years after conversion, but again this field trial did not have randomized replicates.

Management Effects on Fruit and Wine Sensory Characteristics

Berries derived from the long-term trial in Australia on Cabernet Sauvignon were submitted to berry sensory analysis in order to assess grape sensory pulp properties. Berries from organic management resulted in having a significantly higher pulp juiciness compared to berries from the conventional treatment in the third year of conversion (Coffey 2010).

Results concerning the sensory characteristics of wines derived from organic and conventional management are heterogenic. Wines derived from several field trials revealed no influence of management on wine sensory characteristics when rank sum tests were applied

(Danner 1985, Kauer 1994, Meißner 2015). Martin and Rasmussen (2011) compared pairs of organically and conventionally grown wines which differed in their total polyphenol concentration but found no difference in the sensory characteristics. Dupin et al. (2000) compared commercially available wines of organic and conventional production and did not observe differences in the wine sensory attributes. However, in two of these studies the wines from conventional management were perceived as more floral, fruity, vegetal and complex (Dupin et al. 2000, Meißner 2015), whereas the wines from biodynamic management tended to be more balanced, full-bodied, with a stronger minerality and more length (Meißner 2015). In this study wines from biodynamic management were preferred by the tasting panels in rank sum tests (Meißner 2015). Wines from the Australian long-term-trial on Cabernet Sauvignon were characterized by quantitative descriptive analysis and wines from organic and biodynamic plots were assessed as more rich, textural, complex and vibrant in comparison to wines from conventionally managed plots (Collins et al. 2015a). Henick-Kling (1995) found wines from organic management (Seyval) to be significantly more spicy and less skunky compared to conventional wines and panelists preferred the wine from organic plots. Organically grown Sangiovese wines from an Italian field trial were described as less adstringent with a higher overall acceptance by the sensory panel (Beni and Rossi 2009). Trebbiano wines from the same trial were described as unbalanced and acid with respect to the organic product (Beni and Rossi 2009).

No differences in sensory characteristics of the wines between organic and biodynamic management could be detected concerning Grüner Veltliner and Sangiovese (Danner 1985, Collins et al. 2015a, Parpinello et al. 2015, Patrignani et al. 2017). By contrast Meißner (2015) reports a sensorial preference of Riesling wines from biodynamic management in comparison to the ones from the organic plots. Ross et al. (2009) could detect differences between Merlot wines from organic and biodynamic plots of a field trial in two out of four years, but sensory characteristics attributed to the different wines were not consistent over the years.

Management Effects on Production Costs and Efficiency

The increase of production costs for organic and biodynamic viticulture assessed in Europe, the US and Australia ranged between 7 and 90% compared to conventional production, although the increase of costs was highly dependent on the size of the winery and the timespan since conversion (Danner 1985, White 1995, Linder et al. 2006, Delmas et al. 2008, Santiago 2010, Santiago and Johnston 2011, Collins et al. 2015b). The increase of production costs was mainly due to yield reduction and higher costs for under-vine weed control as well as compost management, whereas costs for irrigation and canopy management decreased (Santiago 2010, Santiago and Johnston 2011). Wheeler (2006) found input costs as well as labor input costs of organic viticulture to be higher compared to conventional viticulture. In the long-term field trial in Australia organic and biodynamic viticulture produced 74 % and 65 %, respectively, of the gross margins compared to high-input conventional viticulture (Collins et al. 2015b). Guesmi et al. (2012) investigated the productive efficiency of organic and conventional wineries in Catalonia and found organic farms to have higher efficiency ratings than conventional farms in the area, mostly due to improved agricultural performance, better management of their inputs and organic price premiums. Biodynamic viticulture in a spanish study showed substantially lower environmental burdens compared to conventional viticulture determined by life cycle assessment (Villanueva-Rey et al. 2014). The life cycle assessment in this case compares all inputs and outputs (trellis, fertilizers, pesticides, energy, water, field operations and emissions) for a production system, e.g. for producing a certain amount of grapes. It evaluates their environmental impact for different forms of viticulture (Villanueva-Rey et al. 2014). Kavargiris et al. (2009) found total energy inputs, fertilizer and plant protection products application, fuel inputs as well as greenhouse gas emissions to be higher in conventional compared to organic wineries of the same size in Greece. On the other hand grape yield, pomace and ethanol from pomace were also higher in conventional wineries (Kavargiris et al. 2009). According to Delmas et al. (2008) costs for biodynamic grapegrowing are between 10 and 15% higher than for organic grapegrowing. Santiago (2010) found biodynamic wineries in Australia to have only 7% higher operational costs including canopy and under-vine-management costs than organic wineries. The

same study highlighted that large biodynamic wineries had less operational costs per hectare, in some cases even less operational costs per hectare compared to conventional wineries (Santiago 2010). Overall costs for winemaking are similar for conventional, organic, and biodynamic wine (Delmas et al. 2008).

Conclusions

Stimulation of soil nutrient cycling by compost application, the implementation of cover crop mixtures with a wide range of species and denial of mineral fertilizers and herbicides, as practiced in organic and biodynamic viticulture, takes some years to make an impact on nitrogen levels and on microbial activity in the soil. This is why long-term field trials seem to be crucial for a better understanding of the management systems. The contribution of soil microbial communities to soil fertility and the consequences on plant growth, especially in comparison to mineral fertilization, is little understood and needs more scientific attention to characterize the underlying phenomena.

Biodiversity at different trophic levels was enhanced under organic and biodynamic viticulture compared to conventional management. 17 out of 24 studies showed a clear increase in biodiversity under organic and biodynamic viticulture. Pest management strategies, herbicide application, addition of compost as well as the diversity of cover crops seem to mainly influence biodiversity in the biosphere of vineyards. The contribution of an enhanced biodiversity to abundance and biodiversity of antagonistic insects in the vineyard should be further investigated and quantified.

Growth under organic and biodynamic viticulture decreased by 21 %, although single study outcomes were heterogenic. This might be due to different soil water availability in organic viticulture, which might result in a lower physiological performance, especially after full-bloom. It is likely that differences in the root system of the vines or the water availability in the soil due to cover cropping might account for different levels of plant growth regulators such as gibberellic acid, cytokinin and auxin that strongly determine growth and vigor. The mechanisms that influence growth in organic and biodynamic viticulture should be further investigated by assessing hydraulic conductivity, stomatal conductance and phytohormone contents at the same time.

A yield decrease of 18 % in organic and biodynamic viticulture compared to conventional viticulture was observed when all available data from scientific field trials were assessed. Since reproductive development of *Vitis vinifera* is highly sensitive to the water status the lower water availability and the lower physiological performance after full-bloom in the organic and the biodynamic management system might cause yield differences. Since the period from initiation to maturation of winegrapes comprises two growing seasons, early season water deficit might have implications for cluster weight of the current year and the number of clusters of the subsequent year. More information about the influence of differing soil moisture content and physiological performance of the management systems on fruit set should be gained in the future.

Treatments did not differ in total soluble solids in juice. It was shown that growth as well as yield of grapevines under organic and biodynamic management generally decreases. One very important parameter determining potential levels of total soluble solids in grape juice is the leaf area/fruit weight-ratio. One reason why organically and biodynamically managed vineyards do not differ from conventional vineyards in total soluble solids in juice could be the simultaneous decrease of growth and yield which results in a similar ratio of leaf area to fruit weight.

Organic and biodynamic treatments showed significantly lower growth, lower canopy density and lower secondary shoot growth. This lower vigor might induce higher levels of flavonoids, anthocyanins and thus a higher antioxidant potential due to greater light exposure. However, just two out of four studies found anthocyanin and flavonoid content in berry skin as well as polyphenol contents in wine to differ between organic and conventional management. Further investigations are necessary to understand possible interactions among management systems, trellis systems and varieties.

A lot of studies that assessed wine quality and wine sensory characteristics among conventional, organic and biodynamic viticulture are inconsistent in their findings. More research is needed on grape, juice and wine compositional analysis to better understand how differences of sensory characteristics perceived by several panels in quantitative descriptive analyses can be supported with reasons. Grapes, juices and wines from replicated field trials with

representative distribution of plots should be used for this to clearly relate the outcome to the different management practices.

Still studies included into the meta-analysis were partially heterogenic and limited in number. Moreover, some locations such as Europe were overrepresented in the meta-analysis due to data availability and frequency of trials in this area comparing conventional and organic viticultural production. Authors nonetheless did not assess any interactions between location of the trials and treatments, but locations differed in their growth level, yield level and level of total soluble solids in juice. This is why when calculating the ratio of organic to conventional growth rate, yield and total soluble solids European results were overestimated.

Future research should concentrate on the optimization of organic and biodynamic viticultural practices in the different environments concerning macronutrient supply, disease incidence, yields and cost structure. One focus of future research should be how to increase biodiversity in perennial cropping system comparing them to habitats that are not used agriculturally. The impact of an increase in biodiversity on vine pests and diseases to determine the benefits of these ecosystem services is one other major issue for future research. On the other hand possible interactions of the management systems with different varieties, trellis systems, soil types, rootstocks and irrigation regimes should be detected in order to determine more effective viticultural management systems.

The comparison of biodynamic and organic viticulture showed similar characteristics. Two recent studies on organic and biodynamic viticulture observed significantly lower pre-dawn water potentials in the biodynamic plots. One of the two studies observed lower stomatal conductance of the biodynamic plots. At the same time a significant increase in leaf enzymatic activity of the biodynamic plots for Sangiovese was observed. One hypothesis is that especially the horn silica preparation 501 made from quartz powder might upregulate plant defense mechanisms attributed to induced plant resistance. This again might have implications for berry composition under biodynamic management. These hypotheses need confirmation, especially because the only study that assessed these phenomena until now did not have randomized field replicates. This is why these observations cannot be clearly attributed to the biodynamic treatment.

In the viticultural trials included in this study the application of the biodynamic preparations was one characteristic of the biodynamic plots, but livestock which is one essential component of a biodynamic farm was not included. It is very difficult to include this in randomized scientific field trial. On-farm experiments with a scientific setup might be more suitable in order to depict biodynamic farming and to draw conclusions on this specific management system.

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1359 **Table 1** Main ingredients of the biodynamic preparations 500 to 507 (adapted from Reeve et al. 2005).

Preparation	Main ingredient	Use
horn manure (500)	cow (<i>Bos taurus</i>) manure	field spray
horn silica (501)	finely ground quartz silica	field spray
yarrow (502)	yarrow blossoms (<i>Achillae millefolium</i> L.)	compost
chamomile (503)	chamomile blossoms (<i>Matricaria recutita</i> L. or <i>Matricaria chamomilla</i> L.)	compost
stinging nettle (504)	stinging nettle shoots and leaves (<i>Urtica dioica</i> L.)	compost
oak bark (505)	oak bark (<i>Quercus robur</i> L.)	compost
dandelion (506)	dandelion flowers (<i>Taraxacum officinalis</i> L.)	compost
valerian (507)	valerian flower extract (<i>Valeriana officinalis</i> L.)	compost

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Table 2 Effects of organic viticulture in comparison to conventional viticulture grouped by different fields of interest.

field of interest	parameters	effect compared to integrated/ conventional management	management system	References
soil	biological activity, feeding activity of soil organisms, soil organic matter, total K	increase	org	Coll et al. 2011, Freitas et al. 2011, Gehlen 1988, Okur et al. 2009, Reinecke et al. 2008
	soil organic C content, total N, P, S, microbial biomass C during conversion	no difference	biodyn	Collins et al. 2015b, Probst et al. 2008, Wheeler 2006
	microbial biomass C, C_{mic}/C_{org} , soil respiration after conversion	increase	org biodyn	Collins et al. 2015b, Freitas et al. 2011, Gehlen 1988, Okur et al. 2009, Probst et al. 2008
	soil compaction	increase	org	Coll et al. 2011
	metabolic quotient q CO ₂	decrease	org biodyn	Freitas et al. 2011, Probst et al. 2008
	mineralized N during conversion	no difference	org biodyn	Coll et al. 2011, Meißner 2015
	mineralized N after conversion	increase	org biodyn	Döring et al. 2015
	Cu content in soils	no difference	org biodyn	Coll et al. 2011, Probst et al. 2008, Radic et al. 2014, Strumpf et al. 2011
	Cu content in soils	increase	org	Beni and Rossi 2009
	soil moisture	decrease	org biodyn	Collins et al. 2015b
biodiversity	arbuscular mycorrhizal fungi, bacterial biodiversity in topsoil, fungal diversity on leaves, shoots and grapes, fungal species richness on bark and grapes, yeast species abundance in must	increase	org biodyn	Bagheri et al. 2015, Freitas et al. 2011, Hendgen et al. submitted, Morrison-Whittle et al. 2017, Radic et al. 2014, Schmid et al. 2011
	fungal species richness in soil, epiphytic microbial communities on grapes, fungal community composition in harvested juice	no difference	org biodyn	Bagheri et al. 2015, Hendgen et al. submitted, Kecskeméti et al. 2016, Morrison-Whittle et al. 2017
	yeast abundance on grapes	decrease	biodyn	Guzzon et al. 2016
	plant species richness, perennial plant species, earthworm abundance, nematode density, biodiversity and abundance of predatory mites, species richness of butterflies, biodiversity and abundance of arthropods, ladybird abundance, detritivore abundance, colembola abundance, spider biodiversity, feeding ecology of birds	increase	org biodyn	Caprio et al. 2015, Caprio and Rolando 2017, Coll et al. 2011, Collins et al. 2015b, Fleury and Fleury 2016, Isaia et al. 2006, Meißner 2015, Nascimbene et al. 2012, Peverieri et al. 2009, Puig-Montserrat et al. 2017, Wheeler 2006
	plant diversity and abundance, plant species composition, moth biodiversity, insect pollination, spider biodiversity and abundance, biodiversity and abundance of birds	no difference	org	Assandri et al. 2016, Brittain et al. 2010, Bruggisser et al. 2010, Nascimbene et al. 2012, Puig-Montserrat et al. 2017
	endogeic earthworm density and biomass, abundance of predatory mites, biodiversity of grasshoppers, biodiversity of ladybirds	decrease	org	Bruggisser et al. 2010, Coll et al. 2011, Fleury and Fleury 2016, Linder et al. 2006
growth	ratio yield/pruning weight	no difference	org biodyn	Collins et al. 2015b
	ratio leaf area/fruit weight	no difference	org biodyn	Döring et al. 2015
	pruning weight, shoot length, canopy density	decrease	org biodyn	Collins et al. 2015b, Corvers 1994, Döring et al. 2015, Hofmann 1991, Kauer 1994, Malusà et al. 2004, Meißner 2015, Pike 2014
	leaf area index (LAI)	no difference	org	Corvers 1994
	leaf area index (LAI)	decrease	org biodyn	Döring et al. 2015
	macronutrient supply in leaves (veraison), chlorophyll content (full-bloom)	no difference	org biodyn	Collins et al. 2015b, Döring et al. 2015, Linder et al. 2006, Meißner 2015
	nitrogen content in leaves (veraison)	increase	org biodyn	Döring et al. 2015
	nitrogen content in leaves, nutrient supply	decrease	org biodyn	Danner 1985, Malusà et al. 2004
	chlorophyll content (veraison), Mg and P contents in leaves or petioles	decrease	org biodyn	Collins et al. 2015b, Döring et al. 2015, Meißner 2015
	physiological performance [A, E, gs]	decrease	org biodyn	Döring et al. 2015
	pre-dawn water potential Ψ_{pd}	decrease	biodyn	Döring et al. 2015
	stem water potential before harvest	no difference	org biodyn	Collins and Döring unpublished
yield		decrease	org biodyn	Collins et al. 2015a, Corvers 1994, Danner 1985, Döring et al. 2015, Danner 1985, Hofmann 1991, Kauer 1994, Malusà et al. 2004, Meißner 2015, Pool and Robinson 1995, Wheeler 2006
		no difference	org	Danner 1985
	berry weight	no difference	org	Corvers 1994, Pool and Robinson 1995
	berry weight, compactness of bunches	decrease	org biodyn	Collins et al. 2015b, Döring et al. 2015, Linder et al. 2006, Meißner 2015, Pool and Robinson 1995
	number berries per bunch, average bunch weight	decrease	org biodyn	Corvers 1994, Collins et al. 2015b, Döring et al. 2015
		no difference	org	Pool and Robinson 1995

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field of interest	parameters	effect compared to integrated/ conventional management	management system	References
disease incidence	disease incidence <i>Plasmopara viticola</i>	no difference	org biodyn	Danner 1985, Pike 2014
		increase	org biodyn	Döring et al. 2015
	disease incidence <i>Erysiphe necator</i>	increase	org	Linder et al. 2006
		increase	org biodyn	Danner 1985, Döring et al. 2015
	disease incidence <i>Botrytis cinerea</i>	no difference	org biodyn	Danner 1985, Meißner 2015, Pike 2014
	disease incidence sour rot, root necrosis (fungal pathogens)	decrease	org biodyn	Döring et al. 2015, Lotter et al. 1999, Meißner 2015
winegrape quality	berry composition	no difference	org biodyn	Collins et al. 2015a, Collins et al. 2015b, Danner 1985, Döring et al. 2015, Henick-Kling 1995, Hofmann 1991, Kauer 1994, Linder et al. 2006, Malusà et al. 2004, Tassoni et al. 2013, Tassoni et al. 2014, Wheeler 2006
	Fe and Zn in berries	increase	org	Coffey 2010
	volatile acidity and malic acid	increase	org	Beni and Rossi 2009
	juice acidity, citric acid in wines	decrease	org biodyn	Corvers 1994, Meißner 2015, Tobolková et al. 2014
	juice and wine quality	no difference	org biodyn	Danner 1985, Dupin et al. 2000, Granato et al. 2015b, Granato et al. 2015c, Granato et al. 2016, Henick-Kling 1995, Kauer 1994, Meißner 2015
	juice quality (by image forming methods)	increase	org biodyn	Fritz et al. 2017
	yeast available nitrogen	increase	biodyn	Döring et al. 2015
		no difference	org biodyn	Collins et al. 2015b, Meißner 2015
	anthocyanin and flavonoid content in berry skin, putrescine (biogenic amine) in wines	increase	org	Malusà et al. 2004, Yildirim et al. 2007
	polyphenol content, antioxidant potential (grapes, juice and wine), phenolic acids, enzyme polyphenol oxidase, <i>trans</i> -resveratrol	increase	org biodyn	Buchner et al. 2014, Dani et al. 2007, Granato et al. 2015a, Micelli et al. 2003, Malusà et al. 2004, Nuñez-Delgado et al. 2005, Otreba et al. 2011, Rodrigues et al. 2012, Tintunen and Lehtonen 2001, Vrček et al. 2011, Yildirim et al. 2004
	alcohol content, total anthocyanins, polyphenol profile grapes and wines, carotenoids, colour density in wine, <i>trans</i> -resveratrol, p-coumaric acid, antioxidant activity, biogenic amines	no difference	org biodyn	Bunea et al. 2012, Collins et al. 2015a, Collins et al. 2015b, Garaguso and Nardini 2015, Lante et al. 2004, Mulero et al. 2009, Mulero et al. 2010, Tassoni et al. 2013
	polyphenol content, antioxidant activity in wine, Cu and Fe in wines, ascorbic acid equivalents, ferric-reducing power	decrease	org	Beni and Rossi 2009, Tobolková et al. 2014, Yildirim et al. 2004
sensory characteristics	berry sensory analysis - pulp juiciness	increase	org	Coffey 2010
	wine sensory characteristics	no difference	org biodyn	Danner 1985, Dupin et al. 2000, Kauer 1994, Meißner 2015
	sensory attributes "floral, fruity, vegetal, complex, skunky, adstringent"	decrease	org biodyn	Beni and Rossi 2009, Dupin et al. 2000, Henick-Kling 1995, Meißner 2015
	sensory attributes "balance, full-bodied, minerality, length"	increase	biodyn	Beni and Rossi 2009, Meißner 2015
	sensory attributes "rich, textural, complex, vibrant, spicy"	increase	org biodyn	Collins et al. 2015
	sensorial preference of tasting panel (ranking)	increase	biodyn	Beni and Rossi 2009, Henick-Kling 1995, Meißner 2015
costs and efficiency	production costs and operational costs, productive efficiency	increase	org biodyn	Danner 1985, Delmas et al. 2008, Guesmi et al. 2012, Linder et al. 2006, Santiago 2010, Santiago and Johnston 2011, Wheeler 2006, White 1995
	environmental impact, total energy inputs, greenhouse gas emissions	decrease	org biodyn	Kavargiris et al. 2009, Villanueva-Rey et al. 2014

Table 3 Effects of biodynamic viticulture in comparison to organic viticulture.

field of interest	parameters	effect compared to organic management	management system	References
soil and biodiversity	soil quality, mineralized N, microbial efficiency in soil, epiphytic microbial communities, arthropods	no difference	biodyn	Döring et al. 2015, Keeskeméti et al. 2016, Reeve et al. 2005, Meißner 2015
	earthworm abundance	increase	biodyn	Meißner 2015
growth		decrease	biodyn	Reeve et al. 2005
	ratio yield:pruning weight	no difference	biodyn	Collins et al. 2015b
	pruning weight, LAI, leaf-area-to-fruit-weight-ratio, macronutrients in leaves, chlorophyll content, physiological performance	no difference	biodyn	Döring et al. 2015, Meißner et al. 2015, Reeve et al. 2005
		no difference	biodyn	Döring et al. 2015
	stomatal conductance	decrease	biodyn	Botelho et al. 2015
	leaf enzymatic activity, intrinsic WUE	increase	biodyn	Botelho et al. 2015
	pre-dawn water potential Ψ_{pd}	decrease	biodyn	Botelho et al. 2015, Döring et al. 2015
yield		no difference	biodyn	Botelho et al. 2015, Döring et al. 2015, Meißner 2015, Reeve et al. 2005
		decrease	biodyn	Danner 1985
	clusters per vine, cluster weight, cluster compactness, berry weight	no difference	biodyn	Döring et al. 2015, Meißner 2015, Reeve et al. 2005
disease incidence	disease frequency <i>Plasmopara viticola</i> , <i>Botrytis cinerea</i>	no difference	biodyn	Danner 1985, Döring et al. 2015, Pike 2014
	disease frequency <i>Botrytis cinerea</i>	decrease	biodyn	Danner 1985
winegrape quality	grape composition and wine quality	no difference	biodyn	Danner 1985, Döring et al. 2015, Granato et al. 2015a, Granato et al. 2015b, Laghi et al. 2014, Meißner 2015, Parpinello et al. 2015, Partignani et al. 2017, Picone et al. 2016, Reeve et al. 2005, Tassoni et al. 2013, Tassoni et al. 2014
	juice quality (by image forming methods)	increase	biodyn	Fritz et al. 2017
	γ -aminobutyric acid, amino acids, organic acids, total phenols, total anthocyanins, <i>trans</i> -caffeic acid	increase	biodyn	Laghi et al. 2014, Picone et al. 2016, Reeve et al. 2005
	juice acidity, sugars, alcohol content, phenolic compounds, wine colour, total polymeric pigments, tannins, glutamine, coumaric acid, <i>trans</i> -caffeic acid	decrease	biodyn	Laghi et al. 2014, Meissner 2015, Parpinello et al. 2015, Picone et al. 2016
sensory characteristics	wine sensory characteristics, sensorial preference	no difference	biodyn	Danner 1985, Martin and Rasmussen 2011, Parpinello et al. 2015, Partignani et al. 2017, Ross et al. 2009
	sensorial preference of tasting panel (ranking)	increase	biodyn	Meißner 2015
costs	production costs	increase	biodyn	Danner 1985, Delmas et al. 2008
	operational costs (under-vine + canopy)	no difference	biodyn	Santiago 2010

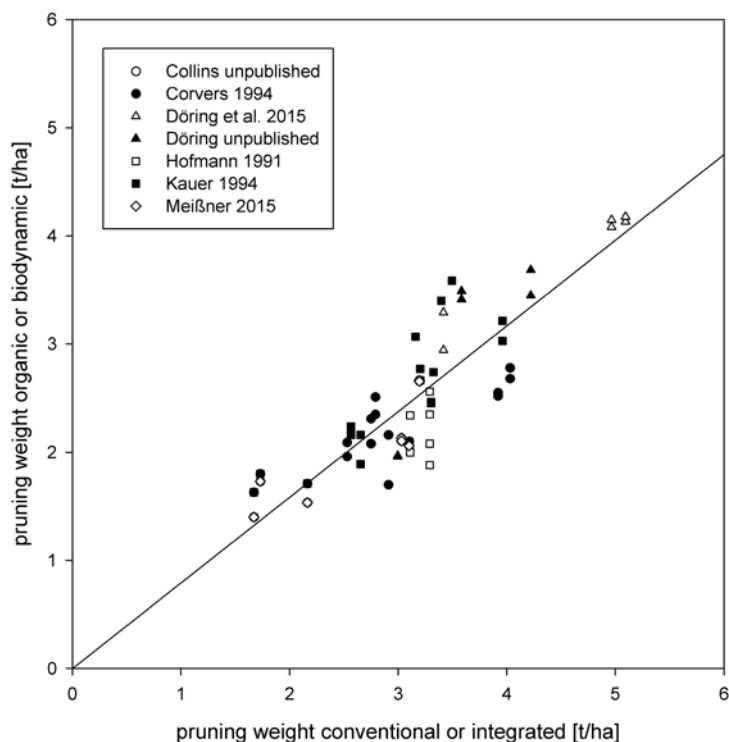


Figure 1 Growth expressed as pruning weight of conventionally and organically or biodynamically managed vineyards ($y = 0.7921x$; $R^2 = 0.74$; $n = 56$).

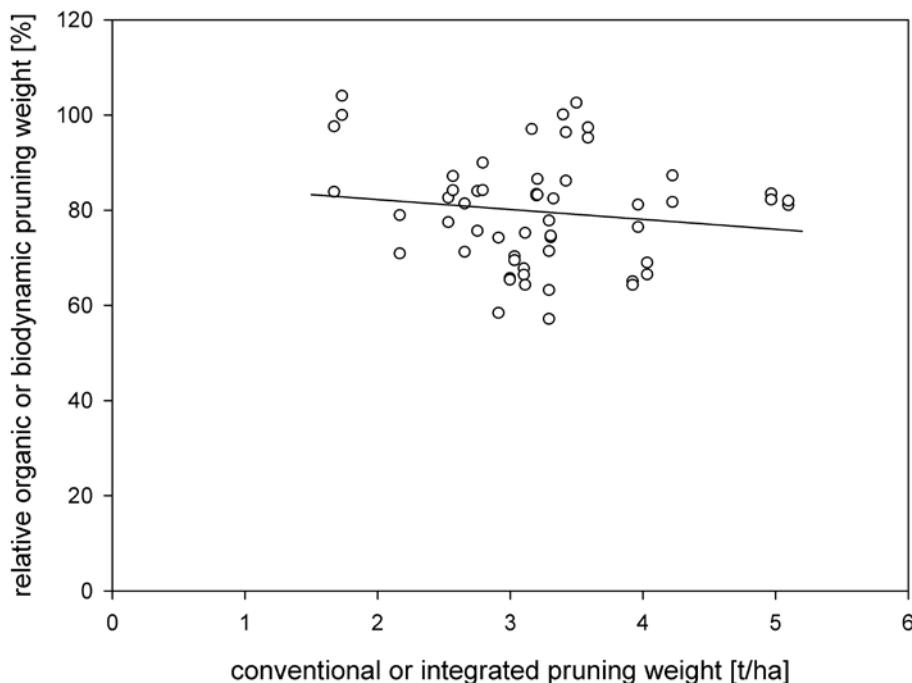


Figure 2 The relative growth expressed as pruning weight of organic viticulture as a function of the absolute conventional or integrated growth expressed as pruning weight from field experiments ($y = -2.0791x + 86.389$; $R^2 = 0.0201$; $n = 56$).

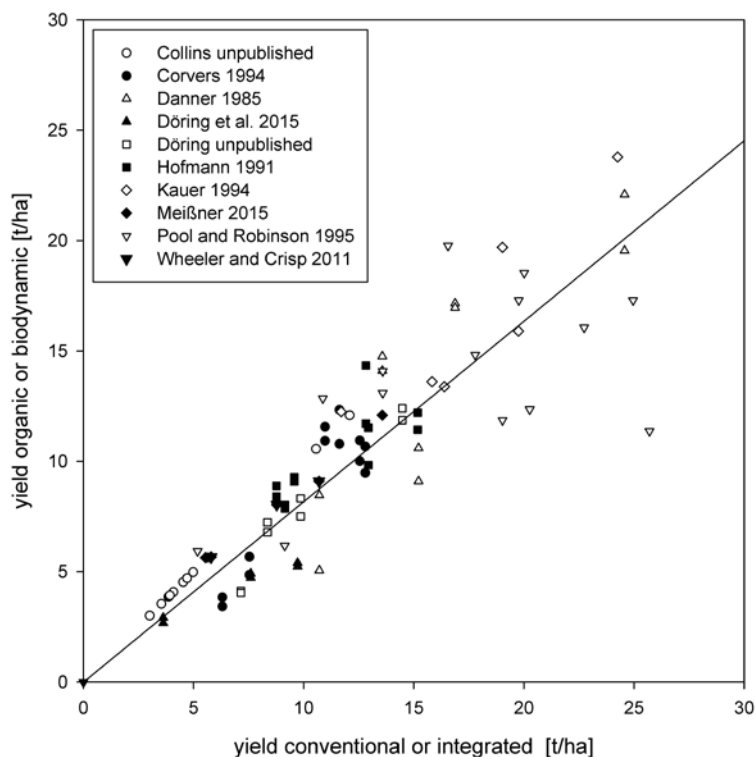


Figure 3 Yield of conventionally and organically or biodynamically managed vineyards ($y = 0.8184x$; $R^2 = 0.80$; $n = 92$).

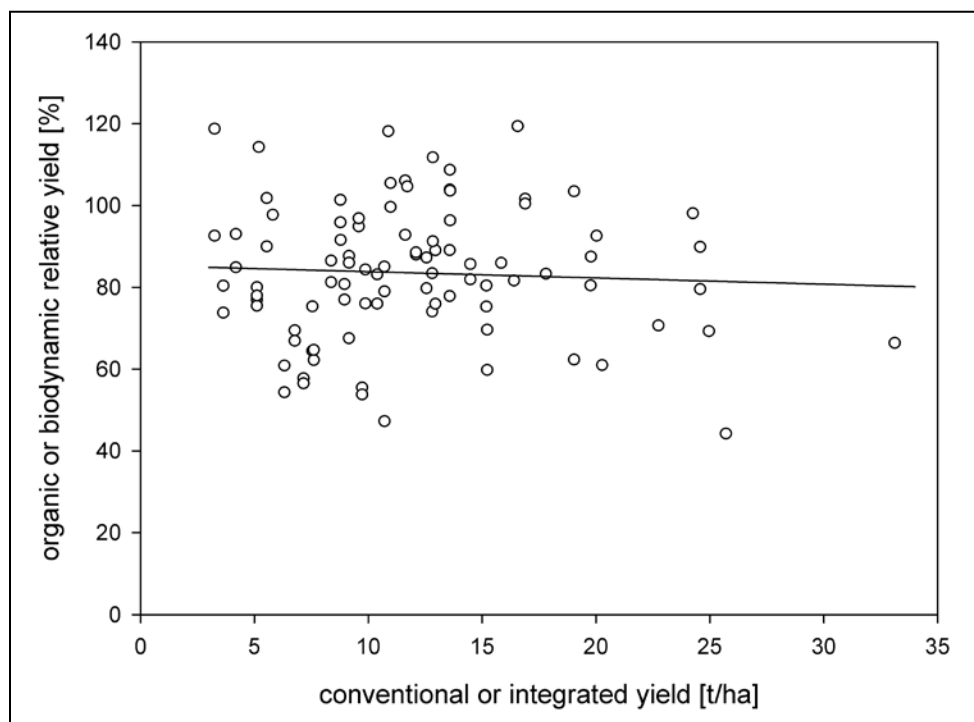


Figure 4 The relative yield of organic viticulture as a function of the absolute conventional or integrated yield from field experiments ($y = -0.1526x + 85.348$; $R^2 = 0.003$; $n = 92$).

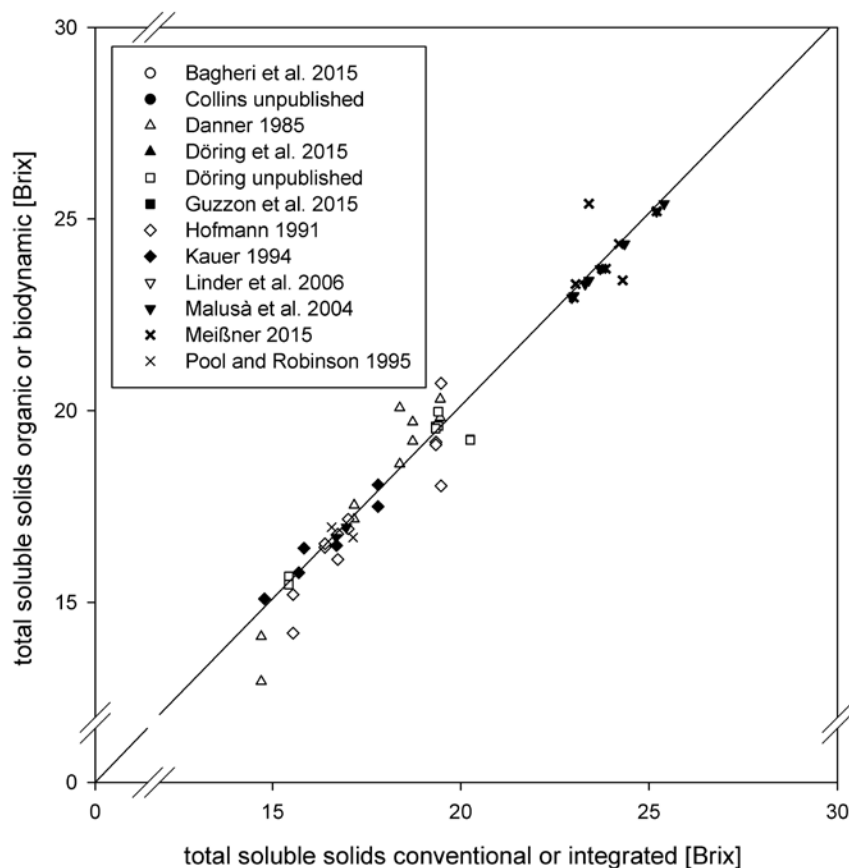


Figure 5 Juice sugar concentration of conventionally and organically or biodynamically managed vineyards ($y = 1.0068x$; $R^2 = 0.96$; $n = 85$).

Supplemental Table 1 Characteristics of the studies included in the meta-analyses and meta-regressions.

Authors	Study years	Number of study years included	Location	Varieties
Bagheri et al. (2015)	2012-2013	2	South Africa	Cabernet Sauvignon
Botelho et al. (2015)	2011-2013	3	Italy	Sangiovese
Collins unpublished	2009-2014	6	Australia	Cabernet Sauvignon
Corvers (1994)	1990-1992	3	Germany	Riesling, Kerner
Danner (1985)	1979-1983	5	Austria	Grüner Veltliner
Döring et al. (2015)	2010-2012	3	Germany	Riesling
Döring unpublished	2013-2016	4	Germany	Riesling
Guzzon et al. (2015)	2014	1	Italy	Pinot blanc and Riesling
Hofmann (1991)	1987-1989	3	Germany	Riesling, Kerner
Kauer (1994)	1989-1991	3	Germany	Riesling, Müller-Thurgau
Linder et al. (2006)	1998-2005	8	Switzerland	Chasselas
Malusà et al. (2004)	2000	1	Italy	Grignolino
Meißner (2015)	2006-2009	4	Germany	Riesling
Picone et al. (2016)	2009, 2011	2	Italy	Sangiovese
Pool and Robinson (1995)	1990-1994	5	US	Concord, Elvira, Seyval
Reeve et al. (2005)	2000-2003	4	US	Merlot
Wheeler and Crisp (2011)	1992-2006	15	Australia	Cabernet Sauvignon, Merlot, Shiraz, Chardonnay

Supplemental Table 2 Results of the balanced fixed factorial analysis of variance (ANOVA) and post-hoc-test (Tukey-Test) for the analysis of pruning weight, yield, and total soluble solids in juice comparing integrated or conventional and organic or biodynamic viticulture.

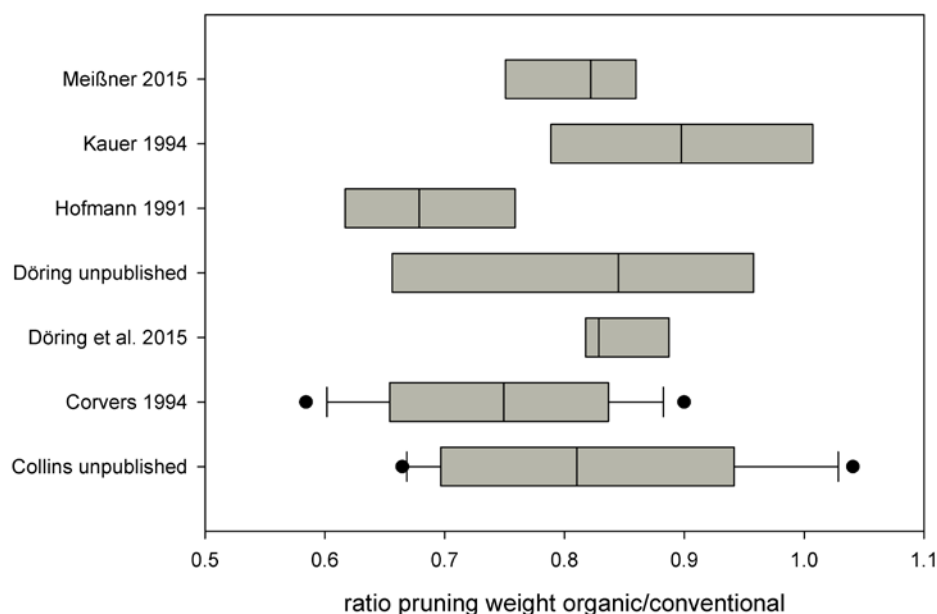
Parameter	Treatment ^a	Int ^b (mean ± sd)	Org ^c (mean ± sd)	Continent	Interactions
Pruning wt (t/ha)	***	3.22 ± 0.79 a ^d	2.55 ± 0.71 b	***	ns
Yield (t/ha)	**	11.94 ± 5.84 a	9.92 ± 4.99 b	***	ns
Juice sugar concn (Brix)	ns	18.77 ± 3.59 -	18.91 ± 3.67 -	***	ns

^a *, ** and *** indicate statistical significance ($p < 0.05$; $p < 0.01$ and $p < 0.001$) of the main effects determined by ANOVA (ns = not significant).

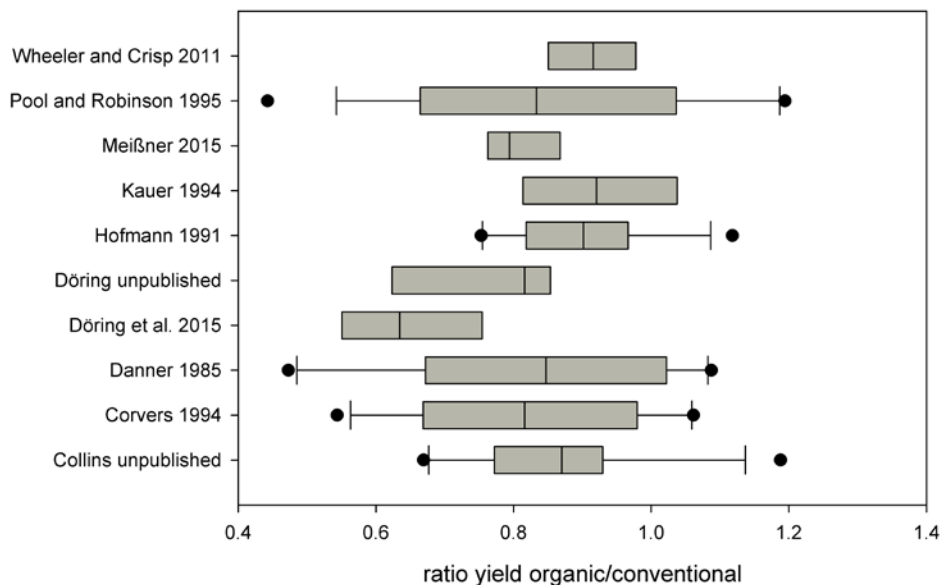
^b Int = integrated or conventional treatment.

^c Org = organic or biodynamic treatment.

^d Different letters indicate statistically significant differences ($p < 0.05$) for the fixed factor management system determined by Tukey test.

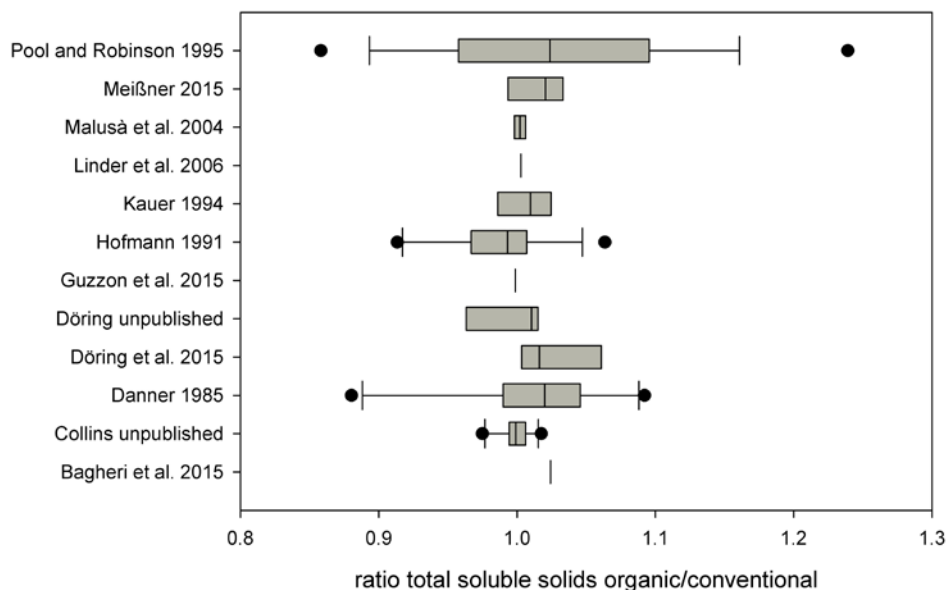


Supplemental Figure 1 Ratio of pruning weight under organic compared to conventional management for every single study included in the meta-analysis and meta-regression. Bars express the distribution of the ratio of pruning weight for organic compared to conventional viticulture for every single study. Median with quantile 25 and 75 and quartile 0 and 1, respectively. Outliers are expressed as dots.



Supplemental Figure 2

Ratio of yield under organic compared to conventional management for every single study included in the meta-analysis and meta-regression. Bars express the distribution of the ratio of yield for organic compared to conventional viticulture for every single study. Median with quantile 25 and 75 and quartile 0 and 1, respectively. Outliers are expressed as dots.



Supplemental Figure 3

Ratio of total soluble solids under organic compared to conventional management for every single study included in the meta-analysis and meta-regression. Bars express the distribution of the ratio of total soluble solids in juice for organic compared to conventional viticulture for every single study. Median with quantile 25 and 75 and quartile 0 and 1, respectively. Outliers are expressed as dots.