



Overcoming yield gaps in organic and biodynamic viticulture: insights from an 18-year field trial

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Abstract

Addressing environmental degradation and fostering agricultural sustainability are critical challenges of the twenty-first century. Agroecological practices such as organic and biodynamic farming are vital for transforming agriculture and enhancing ecosystem services by avoiding synthetic inputs. While often criticized for lower yields, little is known about how these systems adapt and perform over extended periods under varying climatic conditions, particularly for perennial crops such as grapevines. This represents a major knowledge gap, as understanding their long-term adaptive capacity is essential for designing resilient and sustainable production systems under climate change. This 18-year field trial in Geisenheim, Germany, addresses this gap by assessing the long-term effects of organic, biodynamic, and integrated management on *Vitis vinifera* cv. Riesling. It represents the only long-term study on perennial crops to systematically compare these systems' impact on agronomic parameters, plant performance, and grape quality, observing their evolution post-conversion and response to climatic variability. Initially, organic (−17%) and biodynamic (−14%) systems showed lower yields and reduced vine vigor compared to integrated management. However, yield gaps narrowed significantly after approximately a decade. Change point analysis revealed improved relative yields in organic and biodynamic plots 8–9 years after conversion, accompanied by stable or improved Ravaz index values. Notably, in hot, dry vintages, organic and biodynamic systems exhibited enhanced yield effect sizes (+2.3% and +9.0%, respectively) and increased yeast-available nitrogen. Conversely, yield gaps persisted in cooler, wetter vintages, likely due to pathogen-induced losses. Nutrient deficiencies were not the primary cause of initial yield reductions, and grape quality parameters showed minimal treatment differences. These long-term findings demonstrate that organic and biodynamic viticulture can overcome initial yield deficits and potentially outperform integrated management under increasingly warm, dry conditions. The results highlight the adaptive capacity and climate resilience of agroecological systems, offering a sustainable path for future perennial agriculture.

Keywords Management systems · Viticulture · *Vitis vinifera* · Yield · Grape quality · Long-term study

1 Introduction

One major challenge of agriculture in the twenty-first century is ensuring agricultural production remains within planetary boundaries in order to guarantee the environmental sustainability of food systems (Campbell et al. 2017). Food systems are a major driver of environmental degradation (Foley et al. 2011). Therefore, global efforts are needed to transform agricultural production (Eyhorn et al. 2019). A key challenge in the sustainable intensification of agriculture is to produce increasing amounts of food and feed for a growing global population while reducing environmental impacts such as biodiversity loss, nutrient leaching, and greenhouse gas emissions (Schrama et al. 2018).

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Organic farming is considered a sustainable solution for designing future agroecosystems by harnessing ecosystem services and thus reducing the environmental burdens of agricultural production (Ponisio et al. 2015; Eyhorn et al. 2019). Transformative systems such as organic agriculture based on agroecological principles have sustainability benefits, provide greater ecosystem services, and conserve natural resources (Reganold and Wachter 2016; Seufert and Ramankutty 2017). Intensive agricultural systems, on the other hand, have been shown to have negative environmental impacts such as loss of biodiversity, soil erosion, and pollution (Loos et al. 2014; Campbell et al. 2017).

In contrast, organic agriculture is often criticized for its lower productivity compared to conventional farming. Therefore, organic farming is considered inefficient in terms of land use, and critics fear that the expansion of organic agriculture will result in the conversion of additional ecosystems into agricultural land (Kirchmann et al. 2009; Connor and Mínguez 2012). Yield reduction in organic farming for many crops is one major drawback because sustainability per unit of product and economic performance are substantially reduced by lower yields (Seufert and Ramankutty 2017; Meemken and Qaim 2018). Furthermore, the yield gap between conventional and organic farming plays a major role in the debate over whether or not organic agriculture can potentially feed the growing world population (Muller et al. 2017). However, it has been argued that the evaluation of organic systems should extend beyond yield alone, taking into account additional benefits such as ecosystem services and the conservation of natural resources (Wilbois and Schmidt 2019). In any case, improving the performance of transformative, agroecological systems such as organic farming could be one strategy to increase sustainability in agriculture and food systems (Eyhorn et al. 2019).

Organic agriculture is the most widely practiced alternative to conventional farming and is one of the few legally regulated production systems in farming (Seufert and Ramankutty 2017). Organic agricultural practices are characterized by the exclusion of synthetic inputs such as synthetic pesticides and mineral nitrogen fertilizers, relying instead on ecosystem management and services rather than external inputs (Food and Agriculture Organization 1999; European Parliament and Council of the European Union 2018). Although the organically managed agricultural area in 2023 comprised 98.9 million hectares worldwide corresponding to a share of 2.1% of the world's farmland, organic agricultural surface has experienced a substantial increase in the last two decades (Schlatter et al. 2025).

Numerous meta-analyses have shown that yield in organic farming systems is reduced by an average of 19–25% (Ponti et al. 2012; Seufert et al. 2012; Ponisio et al. 2015; Seufert and Ramankutty 2017). However, the yield gap is highly dependent on crop type and management (Ponisio et al.

2015; Seufert and Ramankutty 2017). Since each crop category is unique in its specific nutrient demands, water stress tolerances, and pest and disease susceptibilities, yield gaps naturally differ among crop types (Wilbois and Schmidt 2019). It is crucial to understand the crop-specific reasons for yield gaps between conventional and organic management in order to design effective agroecological systems with potential benefits for agroecosystem health (Seufert and Ramankutty 2017).

Compared to the current share of organically managed agricultural area across all crops, the share of organically managed grape area (including table and wine grapes) is higher, reaching 7.8% in 2023 worldwide (Schlatter et al. 2025). Several studies have shown that the yield gap between organic and conventional systems tends to be smaller in perennial crops than in annual crops (Seufert et al. 2012; Ponisio et al. 2015; Kniss et al. 2016), while others have reported comparatively lower relative fruit yields in organic systems (Ponti et al. 2012). A meta-analysis assessing the relative yields of organic and biodynamic viticulture, defined as the ratio of organic or biodynamic to conventional or integrated yields, found yields to be 18% lower (Döring et al. 2019). No major differences in yields were found either between conventional and integrated (Collins et al. 2015; Gutiérrez-Gamboa et al. 2019) or between organic and biodynamic viticulture systems, respectively (Reeve et al. 2005; Döring et al. 2015; Botelho et al. 2016; Meißner et al. 2019). Reduced berry weights, bunch weights, and a reduced number of berries per bunch observed under organic viticulture could partially account for the yield gap between conventional and organic management (Corvers 1994; Henick-Kling 1995; Pool 1995; Linder et al. 2006; Döring et al. 2015; Meißner et al. 2019). Lower soil water availability (Collins et al. 2015) as well as an increased infestation with downy mildew (*Plasmopara viticola*) might be further reasons for yield losses in organic viticulture (Döring et al. 2015; Merot et al. 2020). In a recent study from Italy, however, no yield differences between organic and conventional management were found (Morelli et al. 2022).

Regarding crop quality under organic management, distinct outcomes have been reported across various crop types, revealing both positive and potential negative impacts of organic farming. One meta-analysis that included annual crops (including cereals, corn, rice, vegetables) as well as perennial crops and livestock products (including poultry, pork, and beef) did not detect major differences between conventional and organic products (Dangour et al. 2009). A further meta-analysis reported increased concentrations of secondary metabolites and vitamin C in organically produced fruits and vegetables (Brandt et al. 2011). Research indicates that organic grape cultivation yields fruits with increased levels of antioxidants and polyphenols, enriching their nutritional profile

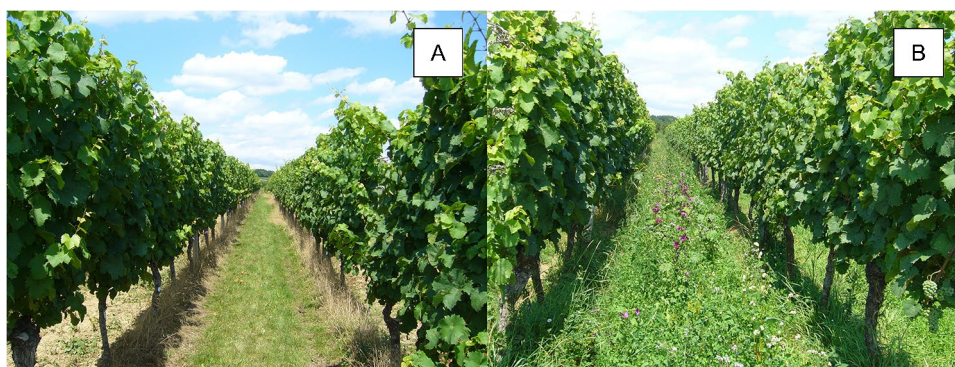


Figure 1 Visual comparison of integrated (A) and organic (B) management within the 18-year-long-term field trial in Geisenheim, Germany. The left side of the image displays the integrated management, characterized by a grass cover in the inter-row and herbicide use in the under-vine area. The right side illustrates the organic

management, distinguished by a diverse, multi-species cover crop in the inter-row and mechanical weeding in the under-vine area. Biodynamic plots, also included in the study, visually resemble the organic plots in their use of multi-species cover crops and mechanical weeding. Photo credit: Johanna Döring.

(Dani et al. 2007; Buchner et al. 2014; Hasanaliyeva et al. 2021; Döring et al. 2022), whereas other studies did not find major differences in berry composition (Malusà et al. 2004; Tassoni et al. 2013, 2014; Döring et al. 2015; Meißner et al. 2019). However, challenges such as increased susceptibility to certain pests and diseases may negatively affect grape quality under organic management in specific vintages (Döring et al. 2015; Merot et al. 2020; Morelli et al. 2022). Agroclimatic parameters such as temperature and water availability throughout the growing season strongly influence fruit composition in grapevine (Ferrer et al. 2017; Beauchet et al. 2020), but no detailed studies to date have examined the interaction between climatic conditions and plant performance under organic, biodynamic, and conventional management.

The aim of this study is to assess the long-term effects of organic, biodynamic, and integrated viticulture management on key agronomic parameters, based on data from an 18-year-long field trial in Geisenheim, Germany. In viticulture, which is one of the most important perennial crops worldwide, a long-term approach is essential due to the longevity of the viticultural system (Alleweldt and Balkema 1965; Monteiro et al. 2021). In the present study, grapevine serves as a perennial model plant to illustrate the long-term effects of different management practices. The current study evaluates various parameters of plant performance as well as grape quality parameters and elucidates how these parameters evolve over time following conversion and how they respond to climatic variability. The study is representative in several respects: it employs a complete block design with four field replicates, the data series spans 18 years, and the findings could inform understanding of the effects of organic and biodynamic management in other perennial cropping systems.

Furthermore, this study seeks to contribute to the broader discussion on the resilience of perennial crop management approaches under changing environmental conditions by examining long-term system performance across a range of climatic conditions. Specifically, it investigates the potential of organic and biodynamic management systems to sustain productivity and grape quality in the face of climatic challenges and to support the development of more resilient agricultural systems.

2 Methods

2.1 Experimental site

The INBIODYN viticulture systems comparison is located in Geisenheim (49° 59'; 7° 56'), Germany. The site has a temperate oceanic climate (Köppen–Geiger Cfb), characterized by mild winters, warm summers (mean of warmest month < 22 °C), and evenly distributed annual precipitation (Kottek et al. 2006). The vineyard was established in 1991 and is planted with *Vitis vinifera* cv. Riesling (clone Gm 198-30), grafted onto *Vitis berlandieri* Planch. × *Vitis riparia* Michx. cv. SO4 and *Vitis riparia* Michx. × *Vitis cinerea* Engelm. cv. Börner rootstocks. It is 0.8 hectares in size and has a row spacing of 2 m and a vine spacing of 1.2 m, with vines trained in a single Guyot system and vertical shoot positioning (VSP) (Fig 1).

The experimental design employs a complete block design with four replicates for each management system. Each main plot comprises four rows with 32 vines per row, with the two outer rows serving as buffer zones to mitigate edge effects.

2.2 Management

Until 2006, the entire vineyard followed Good Agricultural Practice guidelines according to European Union legislation (S.I. No. 393/2022). Beginning in 2006, selected plots within the vineyard were transitioned to organic and biodynamic management, following Regulation (EU) No 2018/848 and ECOVIN and Demeter standards, respectively. The remaining plots continued under integrated management strategies that align with Good Agricultural Practice principles (Table S1).

Cover crops were integrated into all management treatments, with permanent and winter-cover crop mixtures alternating between rows. In the organic and biodynamic plots, multi-species mixtures were used as a permanent ground cover, whereas a grass mixture was sown in the integrated plots. Winter-cover crops consisted of rye and vetch in the integrated plots and winter-hardy, multi-species mixtures in the organic and biodynamic plots. The cover crops were sown according to seasonal conditions.

Every second row in all treatments was plowed shortly before bloom to ensure sufficient nitrogen supply in organic and biodynamic plots by breaking up and incorporating the cover crop mixture rich in legumes. Conversely, to align nitrogen levels with those observed in the organic and biodynamic treatments, integrated plots received targeted applications of mineral fertilizers (25 kg N ha⁻¹ on 2006/07/06, 50 kg N ha⁻¹ on 2010/06/26, 25 kg N ha⁻¹ on 2012/07/05, 25 kg N ha⁻¹ on 2014/06/16, 20.5 kg N ha⁻¹ on 2017/05/30, and 20 kg N ha⁻¹ on 2021/07/02). These applications were made subsequent to soil analyses if reduced nitrogen levels in the integrated plots relative to the organic and biodynamic plots were observed.

Since the conversion, all treatments have been subjected to periodic compost applications in the years 2006, 2007, 2016, and 2021. Integrated plots received composted biological waste, while organic and biodynamic plots utilized composted farmyard manure sourced from organic farming. Additionally, biodynamic compost preparations 502–507 (yarrow (502), chamomile (503), nettle (504), oak bark (505), dandelion (506), and valerian (507)) were applied to the biodynamic compost (Steiner 1998; Masson and Masson 2013). An equivalent amount of nitrogen, as determined by compost analysis, was applied across each treatment to maintain consistency in nitrogen supply.

Under-vine weed control in the integrated plots was managed through biannual herbicide applications, whereas mechanical weeding was employed in the organic and biodynamic plots. For the management of powdery and downy mildew (*Erysiphe necator* and *Plasmopara viticola*, respectively), chemical fungicides were used in the integrated plots. In contrast, the organic and biodynamic plots used a combination of copper, sulfur, and plant strengtheners (Mycosin VIN®, potassium bicarbonate, and sodium

silicate) for mildew prevention. Additionally, across all treatment plots, RAK® 1+2 M (500 dispensers per hectare; containing 178 mg of (E,Z)–7,9-Dodecadienylacetate and 205 mg of (Z)–9-Dodecenylacetate per dispenser) was deployed to manage the vine moth and the European grapevine moth (*Eupoecilia ambiguella* and *Lobesia botrana*) using the mating disruption technique.

The organic and biodynamic treatments shared the same soil and vine management, with the exception that the biodynamic plots also received biodynamic preparations, which were obtained from Dottenfelderhof (Bad Vilbel, Germany) (Steiner 1998; Chalker-Scott 2013; Masson and Masson 2013). Specifically, horn manure and horn silica, known as biodynamic field spray preparations, were applied several times every year. Horn silica was applied three times during critical phenological stages of the grapevine: just before full bloom, at veraison, and prior to harvest. Horn manure was administered two times, around bud break and post-harvest. In years where compost was not applied, the cow pat pit preparation was used once a year at the beginning of the growing season, aligned with tillage activities.

2.3 Yield and grape quality

Crop yield and pruning weight were quantified using gravimetric methods. Crop yield data were obtained at harvest from all vines within the experimental plot, excluding the buffer rows and buffer zones at the top and bottom of each row. Each group of 16 vines was harvested and weighed to calculate the average yield. Pruning weight was assessed during the dormant season each year. Similar to the crop yield, all vines except for the buffer rows were included. The pruning wood per subplot was weighed, and the average weight of 16 vines was determined.

To evaluate juice quality, several key parameters were assessed at harvest using representative whole grape samples. The total soluble solids content of the extracted juice was determined through refractometry. Additionally, pH and total acidity were quantitatively analyzed using Fourier-transform infrared spectroscopy (FTIR) with an FT2 Winescan apparatus (FOSS, Hillerød, Denmark), calibrated in-house. Prior to 2012, pH and total acidity were determined by titration using Titrino 719S (Metrohm, Switzerland). For the quantification of α -amino acids (NOPA), the established method was employed, where α -amino acid groups were derivatized using an o-phthaldialdehyde/N-acetyl-L-cysteine (OPA/NAC) reagent (Dukes and Butzke 1998). Absorbance at 335 nm was measured with a UV/VIS spectrometer (SPECORD 500, Analytik Jena AG, Jena, Germany) against a juice blank. Results were calculated as mg isoleucine equivalent from a standard curve. Mean single berry weight of the samples was determined gravimetrically

shortly before harvest, taking representative maturity samples (100 berries per row, 50 on each side of the canopy).

Infestation with *Botrytis cinerea* on clusters was assessed shortly before harvest according to the EPPO guidelines (European and mediterranean plant protection organisation 2023). For this assessment, 100 randomly selected clusters per variant were evaluated for disease severity, with 50 clusters sampled from each side of the canopy, excluding buffer vines at the row ends.

2.4 Leaf analysis

Macro- and micronutrient content in grapevine leaves was measured at veraison. For this purpose, ten healthy leaves per row opposite to the first inflorescence or the first cluster of a shoot were picked. The leaf blade was washed with distilled water, dried at 60 °C, and ground to a fine powder by Foss Cyclotec™ 1093 (FOSS, Hillerød, Denmark). Of the ground leaf tissue, 0.25 g was used for the wet decomposition procedure. The samples were digested for 1 ½ hours at 100 °C with 10 mL of a mixture of 420 mL H₂SO₄ conc., 330 mL 30% H₂O₂, 0.48 g selenium, and 14 g Li₂SO₄ according to Schaller (Schaller 2000). Samples were analyzed by inductively coupled plasma with optical emission spectroscopy (ICP-OES, Spectro Arcos, Spectro Analytical Instruments GmbH, Kleve, Germany). Standard curves were prepared using a commercial multi-element standard solution (Stammlösung Blatt) containing eight elements in 1 mol L⁻¹ nitric acid (Bernd Kraft GmbH, Duisburg, Germany). Individual readings are the average of two measurements and varied by less than 5%. Nitrogen in the leaf tissue was analyzed by flow injection analysis using a FOSS Tecator FIAstar 5000 Analyzer (FOSS, Hillerød, Denmark).

2.5 Predawn water potential

Predawn water potential was determined on mature, undamaged, and non-senescent leaves using a pressure chamber (Soilmoisture Corp., Santa Barbara, CA, USA) (Scholander et al. 1965; Turner 1988). Prior to the measurements, leaves were wrapped in polyethylene bags and detached from the shoot with a single cut.

2.6 Data management

For an overview of the measured parameters and their respective years of assessment, please refer to the supplementary data (Table S2). Missing data were handled transparently. For predawn water potential measurements, two missing values from 2019 were imputed using linear interpolation based on adjacent time points. In 2022, data were only available for rootstock “Börner”; corresponding values

for “SO4” were imputed using the proportional relationship between the two rootstocks from other measurement years.

2.7 Statistical analysis

Statistical analyses were performed using R (v 4.3) (R Core Team 2024) and its user interface Rstudio (v 2024.09.1+394) (RStudio Team 2024). For all statistical analyses, a significance level of $p < 0.05$ was set. For absolute plant performance and grape quality parameters, normality (Shapiro–Wilk) and homogeneity (Levene’s) were tested using the *car* package (v3.1–3) (Fox and Weisberg 2019). Data meeting these assumptions were analyzed with a linear mixed-effects model (LMM) in *lmerTest* (v3.1–3) (Kuznetsova et al. 2017), specifying treatment, rootstock, year, and their interaction as fixed effects, with block as a random effect. When assumptions were violated, a gamma generalized linear mixed model (GLMM) was fitted using *lme4* (v1.1–35.1.1) (Bates et al. 2015). Post hoc pairwise comparisons were performed with *emmeans* (v1.10.5) (Lenth 2021), applying Satterthwaite’s method for degrees of freedom (Table S3). Relative effect sizes of plant performance and grape quality parameters of treatment x in relation to treatment y in Table S4 and Fig 4 were calculated according to the following equations:

$$\text{Relative effect sizes}_{(x/y)} = -1 \times \left(100 - \left(\frac{\text{Parameter}_x}{\text{Parameter}_y} \times 100 \right) \right) \quad (1)$$

For predawn water potential being negative values, relative effect sizes of treatment x in relation to treatment y were calculated as follows:

$$\text{Relative water potential}_{(x/y)} = 100 - \left(\frac{\text{Water potential}_x}{\text{Water potential}_y} \times 100 \right) \quad (2)$$

Change point analysis was performed using the Change-PointTaylor package (v0.3) (Marks 2024), which provides a straightforward implementation of the change-in-mean detection method originally developed by Wayne Taylor (Taylor 2000). The approach recursively applies the mean square error (MSE) change point calculation to identify candidate change points, as detailed in the package vignette (Marks 2024). For detecting whether time after conversion and GDD_{Bb-H} are positively correlated, a simple linear regression model was applied using the R package datarium (v0.1.0) (Kassambara 2019). All line plots of change point analysis and visualization of the simple linear regression model were generated in R with ggplot2 (v3.5.1) (Wickham 2016). A principal component analysis (PCA) was performed using the FactoMineR package (v2.11) (Husson et al. 2008), thereby centering and scaling all climatic parameters and modeled predawn water

Table 1 Effects of management system on investigated plant performance and grape quality parameters (mean $\pm$ sd) from 2006 to 2023. Analyses of variance were calculated based on linear mixed models. In case normal distribution within the dataset was not given, a gen-

eral linear mixed model was applied. Significant management effects (with $\alpha \leq 0.05$) are marked with *. Average values $\pm$ standard deviation are given.

		Integrated	Organic	Biodynamic
Plant performance	Pruning weight (t ha ⁻¹)	3.46 $\pm$ 0.87^a	2.89 $\pm$ 0.78^b	2.81 $\pm$ 0.77^b
	Yield (kg ha ⁻¹)	9295 $\pm$ 3349^a	7745 $\pm$ 3553^b	7968 $\pm$ 4237^b
	Single berry weight (g)	1.57 $\pm$ 0.47^b	1.46 $\pm$ 0.45^a	1.46 $\pm$ 0.45^a
	Ravaz index	2.77 $\pm$ 1.12	2.93 $\pm$ 1.56	3.09 $\pm$ 1.73
	Predawn water potential (MPa)	-0.22 $\pm$ 0.11^b	-0.26 $\pm$ 0.12^a	-0.28 $\pm$ 0.14^a
	Leaf-N (%)	2.12 $\pm$ 0.27^b	2.20 $\pm$ 0.28^a	2.18 $\pm$ 0.27^a
	Leaf-P (%)	0.34 $\pm$ 0.12^a	0.33 $\pm$ 0.10^a	0.29 $\pm$ 0.07^b
	Leaf-K (%)	0.98 $\pm$ 0.12^b	1.10 $\pm$ 0.15^a	1.10 $\pm$ 0.15^a
	Leaf-Mg (%)	0.24 $\pm$ 0.05	0.24 $\pm$ 0.04	0.23 $\pm$ 0.05
	Leaf-Cu (mg kg ⁻¹)	19.41 $\pm$ 33.57^b	294.64 $\pm$ 128.21^a	298.27 $\pm$ 114.73^a
Grape quality	Severity of <i>Botrytis cinerea</i> (according to EPPO guidelines)	3.70 $\pm$ 1.43	3.69 $\pm$ 1.54	3.65 $\pm$ 1.57
	Total soluble solids (Brix)	19.84 $\pm$ 1.70	19.97 $\pm$ 1.79	19.97 $\pm$ 1.85
	pH	2.97 $\pm$ 0.14^b	2.99 $\pm$ 0.14^{ab}	3 $\pm$ 0.14^a
	Total acidity (g dm ³)	10.81 $\pm$ 2.61	10.8 $\pm$ 2.66	10.81 $\pm$ 2.81
	α -Amino nitrogen (mg dm ³)	78.48 $\pm$ 28.53^b	90.58 $\pm$ 43.62^a	90.79 $\pm$ 40.32^a

potentials (Ψ_{pd}) from 2006 to 2023. Given the perennial nature of grapevines and the physiological relevance of prior-season conditions, the classification included growing degree days (GDD) from flowering to veraison of the preceding year, capturing effects on inflorescence initiation. In addition, the grouping incorporated cumulative annual precipitation and sunshine hours, mean air temperature, and GDD across key phenological stages (budbreak to flowering, flowering to veraison, veraison to harvest) of the current growing season, as well as modeled predawn leaf water potential derived from a soil water balance model (Hofmann et al. 2014), which served as a proxy for vine water status. Modeled predawn water potential was calculated based on the modeled daily relative available water capacity (Hofmann et al. 2014) and applying the van Genuchten water retention model (van Genuchten 1980) with parameters for medium sandy loam (Ls3). The first two principal components were selected for visualization based on the scree plot. K-means clustering (stats package (v 4.3.1) (R Core Team 2024)) was then applied to group vintages, with the Elbow Method (factoextra package (v1.0.7) (Kassambara and Mundt 2016)) indicating an optimal solution of three clusters, subsequently assessed using a silhouette analysis (cluster package (v2.1.4) (Maechler 2018)). Graphical outputs, including correlation circles, variable contributions, and factor maps, were generated using factoextra (v1.0.7) (Kassambara and Mundt 2016) and corrplot (v0.95) (Wei et al. 2021), illustrating both the PCA results and subsequent cluster assignments. For relative effect sizes, normality (Shapiro–Wilk) and homogeneity (Levene’s) were checked

with the car package. Data meeting these assumptions were analyzed using an LMM in lmerTest, specifying vintage group and rootstock as fixed effects, with block as a random effect. Non-normal or heteroscedastic data were instead fitted with a Gaussian GLMM in lme4. Post hoc pairwise comparisons were again performed in emmeans, applying Satterthwaite’s method for degrees of freedom. Relative effect sizes for performance and quality parameters were illustrated using radar charts, implemented via the fmsb package (v0.7.6) (Nakazawa and Nakazawa 2019).

3 Results

3.1 Long-term effects: plant performance and grape quality

The comparison of management systems revealed distinct differences in key plant performance and grape quality parameters over the period from 2006 to 2023 (Table 1, Table S3).

The organic treatment showed 16.4% lower pruning weights, and the biodynamic treatment showed 18.9% lower pruning weights compared to the integrated treatment (34.57 $\pm$ 8.7 dt ha⁻¹). Integrated management also resulted in the highest yields, which were significantly higher than those observed under organic and biodynamic treatments. On average, organic yields were 16.7% lower, and biodynamic yields were 14.3% lower compared to integrated management. In

addition, berry weight was also significantly higher under integrated management (1.57 ± 0.47 g) in comparison to the organic and biodynamic systems (both 1.46 ± 0.45 g). Despite these differences, the Ravaz index (yield per pruning weight), a key measure of vine balance, did not differ significantly among treatments due to parallel reductions in both pruning weights and yields in organic and biodynamic plots. Total soluble solids in juice at harvest showed no significant differences among treatments. Predawn leaf water potential at veraison was significantly higher under integrated management, indicating lower water stress compared to organic and biodynamic treatments.

Leaf analysis of macro- and micronutrient concentrations at veraison revealed significant differences among the management systems. Organic and biodynamic management exhibited higher values for nitrogen (N), potassium (K), and copper (Cu) compared to integrated management. Magnesium (Mg) concentrations did not differ significantly among treatments. Phosphorus (P) concentrations were significantly lower in biodynamic management compared to organic management and integrated management, while integrated and organic treatments did not differ significantly.

Grape juice analysis at harvest also showed significant differences among management systems. NOPA content, a measure of yeast-available nitrogen, was significantly higher under organic and biodynamic management compared to the integrated system. Juice pH at harvest differed significantly between biodynamic and integrated systems, with biodynamic plots showing a higher pH. Total acidity in juice at harvest did not differ significantly among treatments. Furthermore, no significant differences were observed in *Botrytis cinerea* incidence among treatments, despite the application of botryticides in the integrated system twice per vegetation period.

Generally, organic and biodynamic management did not differ in most of the investigated parameters, only for Phosphorus in leaves significantly lower values for biodynamic management in comparison to organic were observed.

3.2 Plant performance in relation to time since conversion

Looking at the dynamics of relative yield effect sizes of organic and biodynamic compared to integrated management from 2006 to 2023, a change point was identified for both organic and biodynamic treatments using change point analysis (Fig 2A).

A change point was detected for both organic and biodynamic treatments in comparison to the integrated treatment, occurring in 2014 and 2015, respectively. These change points were characterized by higher yield effect sizes, indicating a reduction in yield losses 9 and 10 years after initiating the trial. Specifically, for the biodynamic treatment, the

change point in 2015 was statistically significant at the 95% confidence level, with relative yield effect sizes improving from a mean of -27% (2006–2014) to -7% (2015–2023). For the organic treatment, a change point was identified in 2014 at the 90% confidence level, with effect sizes improving from a mean of -28% (2006–2013) to -11% (2014–2023).

For pruning weight, no significant change point was detected across the years from 2006 to 2023, with consistently lower pruning weights for organic and biodynamic systems in comparison to integrated management (Fig 2B).

In terms of the Ravaz index, significant changes were detected during the study period. For the organic treatment, a significant change point was observed in 2010 (at a 95% confidence level), with the relative Ravaz effect size changing from $+3$ to -29% (Fig 2C). Another significant change occurred in 2014 (also at a 95% confidence level), with the effect size improving from -29% to $+17\%$. For the biodynamic treatment, significant changes were detected in 2011 and 2014. In 2011, the relative Ravaz effect size changed significantly from $+1\%$ to -31% (at a 95% confidence level), and in 2014, the effect size improved from -31% to $+26\%$ (at a 95% confidence level).

These findings suggest a temporal relationship between yield effect sizes and relative Ravaz effect sizes of organic and biodynamic treatments, respectively, and the time after conversion. Due to the fact that in the last period of the trial hot and dry vintages seem to occur more frequently, a regression analysis of the years following conversion and the cumulative growing degree days from budburst to harvest (GDD_{Bb-H}) over the period from 2006 to 2023 was conducted. It revealed a significant positive correlation ($p = 0.029$, $R^2 = 0.219$; Fig. S1). This is why it seems likely that the effect of time after conversion is masked by the climatic effect or that both effects overlap.

3.3 Plant performance and grape quality parameters in relation to climate

In order to unravel potential climatic effects on plant performance and grape quality under organic and biodynamic management in comparison to integrated management, growing seasons from 2006 to 2023 were classified based on key agroclimatic parameters (Fig. 3).

Panel A shows the contribution of these variables to the first two principal components of the PCA. Dim1 (38.3% of variance) was driven mainly by temperature-related variables (mean annual temperature, sunshine hours, and GDD across phenological stages), whereas Dim2 (20.7% of variance) was largely explained by precipitation and modeled Ψ_{pd} across the developmental phases. Thus, both heat accumulation and water status emerged as the main factors structuring inter-annual climatic variability. Subsequent K-means clustering grouped years into three distinct vintage groups (Fig. 3B),

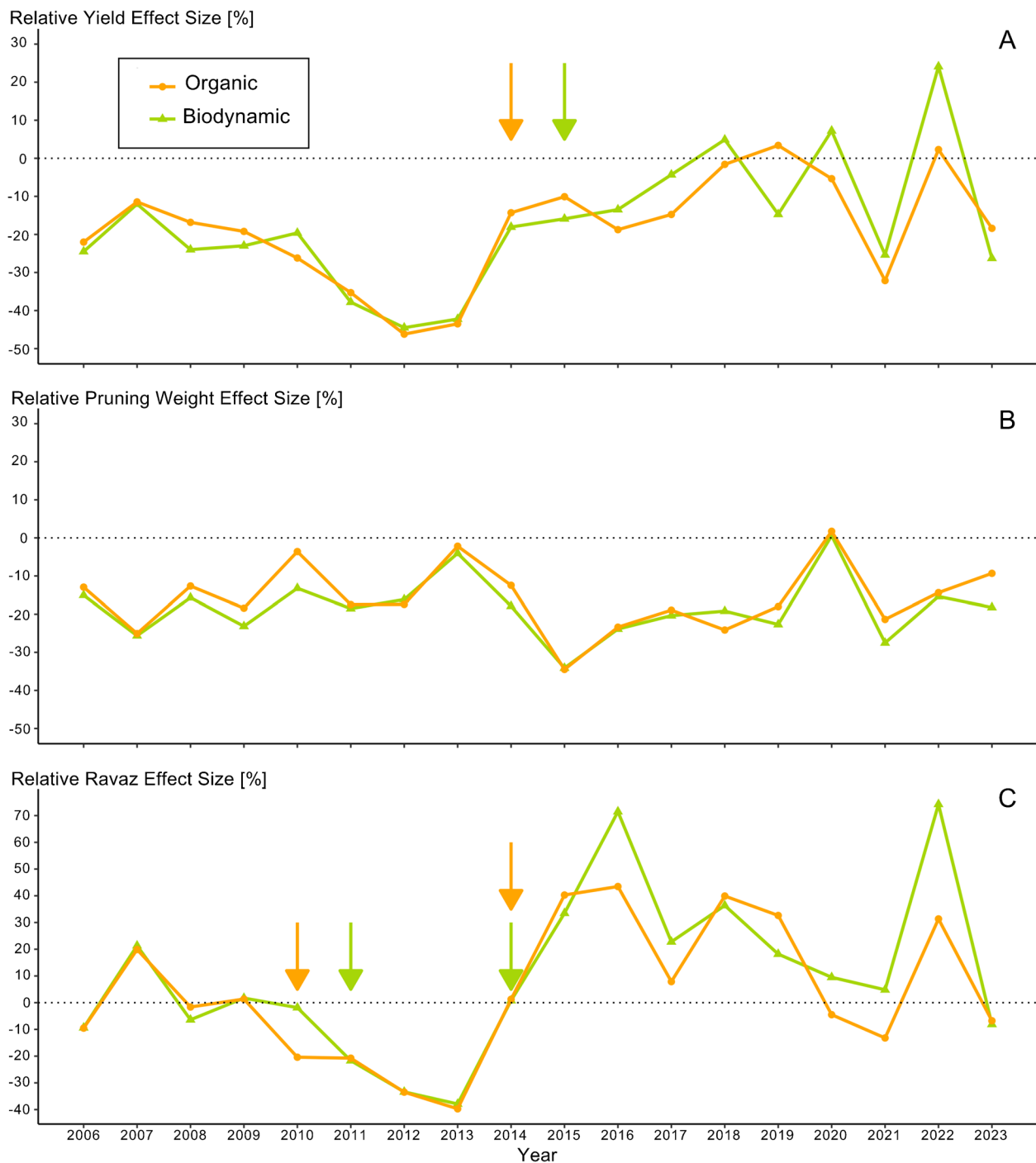


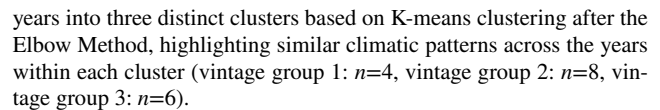
Fig. 2 Relative effect sizes (%) of yield, pruning weight, and Ravaz index in response to biodynamic (bd) and organic (org) treatments compared to integrated management across the years 2006 to 2023. **A** Yield response, with significant change points indicated for

organic (2014) and biodynamic (2015) treatments. **B** Pruning weight response, where no significant change points were detected. **C** Ravaz index response, with two change points identified for organic (2010 and 2014) and biodynamic treatments (2011 and 2014).

reflecting coherent climatic signatures. Climatic conditions differed significantly among the clusters (Fig. S2). Vintage group 1 had higher mean sunshine hours (2050 ± 90 h) than group 2 (1777 ± 77 h) and group 3 (1586 ± 75 h), lower precipitation (473 ± 47 mm) compared to group 3 ($587 \pm$

46 mm), and higher mean temperatures (12.2 ± 0.3 °C) compared to group 3 (10.9 ± 0.8 °C).

Analysis of growing degree days (GDD) and modeled predawn water potential across grapevine development phases showed significant differences among vintage groups



For plant performance parameters like leaf nutrients magnesium (Mg) and potassium (K), as well as grape quality parameter total soluble solids, a significant vintage group effect was observed for both organic and biodynamic systems in comparison to integrated management, with the

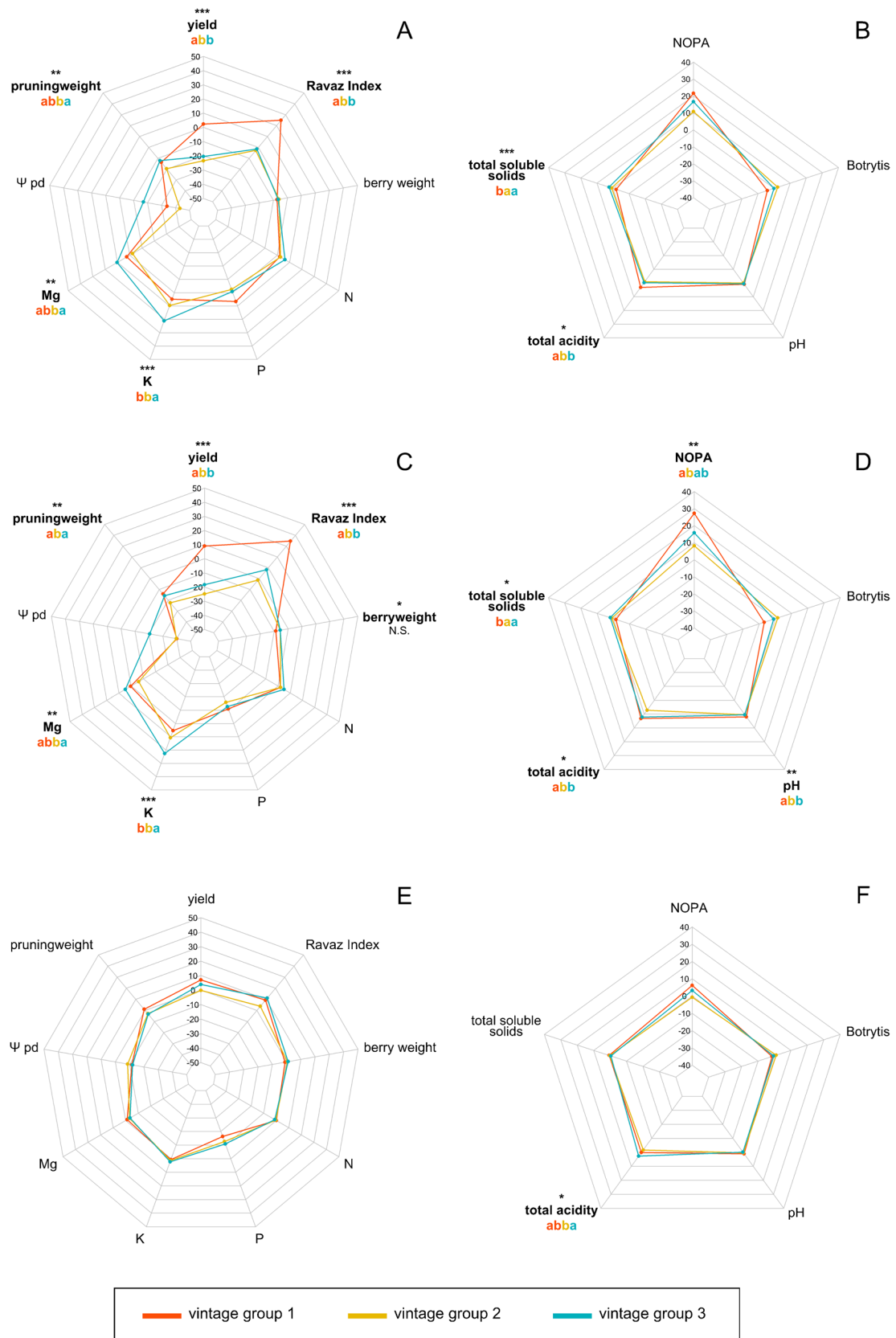


Fig. 4 Relative effect sizes of plant performance (A, C, E) and grape quality (B, D, F) parameters under different management systems across three vintage groups (red = vintage group 1, yellow = vintage group 2, blue = vintage group 3). Subpanels represent comparisons between management systems: A, B = organic in relation to integrated; C, D = biodynamic in relation to integrated; and E, F = biodynamic in relation to organic. Asterisks above each parameter indicate the statistical significance of the vintage group effect (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; N.S. = not significant). Letters below each parameter show pairwise comparisons among vintage groups (different letters = significant difference; N.S. = non-significant even if the main effect is significant). All other model effects are provided in Supplementary Table S2.

highest relative effect sizes occurring in vintage group 3 (Fig. 4A, B and Fig. 4C, D).

Both organic and biodynamic treatments exhibited significantly higher relative effect sizes for total acidity in vintage group 1, while biodynamic management additionally showed a significantly higher relative effect size for pH (Fig. 4B and Fig. 4D). This indicates that, in vintage group 1, higher pH values coincided with increased total acidity under biodynamic management. However, the absolute pH values across all vintage groups remained within a narrow range (2.97 ± 0.14 in integrated to 3.00 ± 0.14 in biodynamic), suggesting that these differences may be of limited practical relevance. No significant differences among all vintage groups were observed for parameters such as leaf nitrogen (N), phosphorus (P), predawn water potential at veraison, and *Botrytis cinerea* incidences (Fig. 4A, B and Fig. 4C, D).

When comparing the relative effect sizes of biodynamic management to organic management, no significant vintage group effect was detected across most parameters (Fig. 4E, F). An exception was found for total acidity, where biodynamic management showed the highest relative effect size in vintage group 3 ($2.7\% \pm 8.9\%$) compared to vintage group 1 ($0.1\% \pm 8.5\%$) and vintage group 2 ($-1.7\% \pm 7.01\%$) in relation to organic management.

4 Discussion

Monitoring effects of organic agriculture and other agroecological approaches across different cropping systems and climates is of major importance to drive the transformation of agriculture across the planet through the adaptation of agroecological systems (Seufert and Ramankutty 2017).

Organic and biodynamic plots in the current study showed lower average yields (org -17% , bd -14%) and lower average pruning weights (org -16% , bd -19%) from 2006 to 2023. These findings are in accordance with other studies describing effects of organic and biodynamic viticulture systems (Collins et al. 2015; Döring et al. 2015, 2019; Meißner et al. 2019) as well as effects in other cropping systems (Ponti et al. 2012; Seufert et al. 2012). The Ravaz index,

an important indicator for vine balance (Ravaz and Sicard 1903; Howell 2001), did not show differences among treatments since growth and yield decreased in parallel under organic and biodynamic viticulture. Typically, an optimal Ravaz index falls between 5 and 10 (Smart 1991), dependent on the variety, with lower values suggesting either strong vegetative vigor or insufficient fruit yield (Santesteban et al. 2010). The absolute values of the Ravaz index were low across all treatments (int: 2.77 ± 1.12 , org: 2.93 ± 1.56 , bd: 3.09 ± 1.73), indicating a tendency towards larger canopy sizes relative to fruit yields.

Nutrient deficiency does not appear to be the primary factor contributing to reduced yield and growth in organic and biodynamic systems. The systems demonstrated higher nitrogen (N) and potassium (K) contents at veraison in leaf tissue, while magnesium (Mg) concentrations in leaves remained comparable across all management practices. At veraison, leaf blade N averaged ~ 2.1 – 2.2% DW across systems, which lies at the lower edge of the sufficiency interval for veraison leaves (2.2 – 4.0% DW) reported by Robinson (1988) and is consistent with earlier observations in Riesling by Loehnertz (1988). Leaf-K (~ 1.0 – 1.1% DW) was well within the veraison sufficiency range (0.8 – 1.6% DW; Robinson 1988), confirming adequate potassium supply in all systems. Leaf-Mg (~ 0.23 – 0.24% DW) was slightly below Robinson's veraison sufficiency band (0.30 – 0.60% DW), but still above levels associated with severe deficiency symptoms. Although the biodynamic system exhibited significantly lower leaf phosphorus (P) than the other treatments, mean values (0.29 – 0.34% DW) remained within or above the sufficiency range for veraison (0.15 – 0.30% DW; Robinson 1988) and well above critical deficiency thresholds identified in other studies (Schreiner and Osborne 2018), indicating adequate P availability in all systems.

Juice analysis at harvest showed that α -amino nitrogen, measured as NOPA (primary amino groups), was higher under organic and biodynamic viticulture practices, suggesting an improved N supply for yeast during alcoholic fermentation (Dukes and Butzke 1998). Optimized cover crop management ensuring mineralization of organic nitrogen compounds into nitrate, together with reduced yields, might account for the better N supply in leaves and berries of organic and biodynamic plots (Abad et al. 2021; Döring et al. 2022). NOPA values in the current study appear generally sufficient, ranging from the lower optimum threshold of around 70 mg N L^{-1} for integrated treatment to higher levels of around 90 mg N L^{-1} for organic and biodynamic plots, thereby meeting recommended thresholds for healthy fermentation (Dukes and Butzke 1998). Leaf copper concentrations were markedly higher in the organic and biodynamic plots ($\sim 295 \text{ ppm}$) than in the integrated system ($\sim 19 \text{ ppm}$), most likely reflecting residues from repeated applications of copper-based fungicides. Similar patterns have been

reported in other vineyards, where multi-year copper use in organic management resulted in substantially elevated foliar Cu (Roviello et al. 2021; Ochmian and Malinowski 2024).

Winegrape quality parameters, including total acidity and total soluble solids, did not differ significantly among the management systems. Although juice pH showed statistically significant differences among treatments, the marginal nature of these differences suggests limited practical relevance. The incidence of *Botrytis cinerea*, a critical factor for winegrape quality, remained consistent across treatments, even though the integrated plots received botryticides twice annually. This suggests that canopy microclimate or looser cluster architecture may have contributed to mitigating infection in the organic and biodynamic systems (Döring et al. 2013, 2015; Meißner et al. 2019).

The temporal development of yield, pruning weight, and the Ravaz index of organic and biodynamic management in relation to integrated management was analyzed in relation to time after conversion, highlighting distinct trends and change points. Change point analysis revealed a significant increase in relative yield effect sizes for both organic and biodynamic systems 8 and 9 years after conversion, respectively. This shift in relative yield effect size is due to yield increases in organic and biodynamic treatments, not due to yield decreases under integrated management.

Although average yields remained significantly lower under organic and biodynamic management compared to integrated management throughout the study period (Table 1), a positive shift in relative yields emerged several years after conversion. This trend is consistent with previous findings showing that yields in organic systems can recover to conventional levels within a few years after an initial decline (Merot et al. 2020). A meta-analysis further supports this pattern, indicating that organic performance improves in studies lasting more than two seasons or on plots managed organically for at least 3 years, supporting the observed long-term yield stabilization in organic and biodynamic systems (Seufert et al. 2012). Still, changes in trends concerning relative yields of organic and biodynamic in relation to integrated viticulture occurred later in the current study. Both the initial drop and later increase in relative Ravaz index effect size of organic and biodynamic in comparison to integrated viticulture are primarily driven by these yield dynamics. The relative effect size of pruning weight remained consistently lower for organic and biodynamic systems across all vintage groups, suggesting that reduced vine vegetative vigor is a robust outcome of organic and biodynamic management independent of the climatic conditions.

The temporal progression of yield and Ravaz index during the study period raises critical questions about the underlying mechanisms driving the observed positive change points under organic and biodynamic management. One key consideration is whether these systems require a transition

or adaptation phase in which soil and ecological processes gradually reach a new equilibrium, implicating time after conversion as a determinant of crop performance and grape quality (Mäder et al. 2002). Moreover, climatic variation may interact with management practices to influence both yields and quality attributes, necessitating an integrated view of environmental drivers. However, the strong correlation between growing degree days (GDD) and time after conversion (Fig. S1) indicates that the apparent influence of time may partly reflect increasing temperatures over time. To clarify these interrelationships, we categorized vintages based on their climatic characteristics, enabling a clearer assessment of how organic, biodynamic, and integrated management systems influence crop performance and grape quality under varying environmental conditions. Such vintage groupings based on temperature and rainfall patterns have been shown to be essential for understanding inter-annual variability in viticulture and its impact on system performance (Renaud-Gentié et al. 2020).

Beyond vegetative growth, the relative effect sizes in yields further differentiate organic/biodynamic from integrated vineyard management under varying climatic conditions. By contrast, vintage groups 2 and 3, encompassing cooler and wetter conditions, were marked by consistently negative yield effect sizes for the organic and biodynamic management. Although direct data on the severity of downy or powdery mildew were not available within this study period, it is plausible that the higher disease pressure in these more humid conditions contributed to yield reductions in the organic and biodynamic plots, given that these systems rely on non-synthetic pest and disease control methods. This aligns with previous findings that suggest pest and disease pressure severities could have been a major cause of yield losses in the initial years following conversion to organic systems (Merot et al. 2020).

Despite a statistically significant difference in total acidity (TA) between organic and biodynamic treatments in vintage groups 2 and 3, the actual magnitude of this difference was minimal, rendering it of limited practical relevance. Beyond this single parameter, no other significant distinctions emerged between organic and biodynamic management across the assessed indicators of plant performance and grape quality across vintage groups. These findings are in accordance with previous studies that also reported only minor or inconsistent differences between organic and biodynamic systems (Reeve et al. 2005; Granato et al. 2015; Döring et al. 2019; Parpinello et al. 2019; Rienth et al. 2023). Even though the lower relative yield effect sizes in organic and biodynamic systems during wetter and colder years could partly be linked to pathogen-induced yield losses, the higher relative yields observed under organic and biodynamic management in hot and dry years (vintage group 1) cannot be solely attributed to reduced disease pressure.

Further differences in plant performance and grape quality parameters were observed under these conditions, indicating additional contributing factors. Generally, in vintage group 1, representing hot and dry conditions, the relative yield effect size in organic/biodynamic compared to integrated treatments increased. This shift in plant performance is reflected by the enhanced relative Ravaz index in organic/biodynamic plots. Concerning grape quality parameters, the higher relative acidity effect size and lower total soluble solids effect size are further symptoms of the enhanced yield performance of organic and biodynamic plots in vintage group 1.

The only parameter which can account for the change in relative yield effect sizes of organic and biodynamic plots under hot and dry conditions is the α -amino nitrogen concentration in juice at harvest expressed by NOPA. The α -amino nitrogen concentration in juice at harvest is enhanced in organic plots under dry and hot conditions and is even significantly enhanced under biodynamic management in vintage group 1. Both organic and biodynamic treatments show positive yield effect sizes in vintage group 1 (+2.3 and +9.0%, respectively), but the positive yield effect size is even more pronounced under biodynamic management, where α -amino nitrogen in juice at harvest is also significantly enhanced. This might indicate that facilitated N uptake might be responsible for the improved yield effect size of organic and especially biodynamic management under hot and dry climatic conditions.

In vintage group 1, N availability or uptake may have been further promoted by greater drought resilience, differences in root architecture, or beneficial microbial communities enhancing water and nutrient acquisition. Long-term adaptations of rooting patterns induced by diverse cover crop mixtures, particularly those rich in legumes, may further contribute to improved resource acquisition (Fichtl et al. 2023). Such soil management strategies in organic and biodynamic viticulture are expected to support a more continuous N mineralization and nitrate supply through the incorporation and subsequent mineralization of legume-rich cover crops (Döring et al. 2022). Moreover, shifts in soil microbial biomass and community composition under organic and biodynamic management (Hartmann et al. 2015; Hendgen et al. 2018; Di Giacinto et al. 2020) could additionally enhance nutrient cycling and resilience under hot and dry conditions. On the other hand, the vegetative growth of integrated management is enhanced even under hot and dry conditions in vintage group 1, potentially leading to lower N availability in berries monitored in the integrated plots compared to organic and biodynamic management. More vigorous canopy development likely diverted a greater share of absorbed nitrogen into vegetative tissues rather than berries, consistent with partitioning studies showing that a substantial proportion of N is retained in

shoots and leaves while only a smaller fraction is allocated to bunches (Conradie 1991). One reason for the enhanced growth under integrated management under hot and dry conditions, possibly preventing higher N accumulation in berries, might be the water availability and water uptake early in the season. The different vintage groups are shaped by similar conditions within the vegetative growth phase from budburst to veraison (no significant differences in GDD and predawn water potential), but show major differences in modeled predawn water potential between veraison and harvest in the generative phase (higher GDD and lower modeled predawn water potential) (Fig. S2). Cover crop management may further contribute to these patterns. In the integrated system, low-biomass grass covers help maintain soil water availability early in the season, thereby supporting grapevine vegetative growth. By contrast, organic and biodynamic systems typically use legume-rich mixtures that generate substantial above- and belowground biomass before budbreak, leading to higher water use early in the season (Fichtl et al. 2023). This increased consumption can reduce soil water availability during the grapevine's vegetative growth phase and limit vine vigor but may also promote adaptive responses that enhance resilience. Higher yields in organic/biodynamic management in vintage group 1 suggest that these management systems can cope better with water stress in the generative developmental stage.

5 Conclusion

Building on this 18-year field trial in Geisenheim, the study evaluated the long-term effects of organic, biodynamic, and integrated viticulture on vine performance and grape quality. This unique long-term comparative study provides valuable insights into how the performance of agroecological systems adapts over time and responds to climatic variability. Our results emphasize the importance of extended monitoring to capture the full trajectory of agroecological systems. Over nearly two decades, organic and biodynamic systems consistently showed reduced yield and vine vigor compared to integrated management, yet the differences in yield diminished significantly around a decade after conversion, particularly in warmer, drier vintages. The results further illustrate the complex interplay between time after conversion and climate, suggesting that organic and biodynamic systems can exhibit improved resilience under late-season water deficits. Although disease-related yield losses in humid vintages remain a concern, ongoing work on soil health, root system development, and microbial ecology may further elucidate the mechanisms by which organic and biodynamic systems adapt to environmental stress.

Overall, these findings highlight the potential of organic and biodynamic management as viable and more sustainable alternatives to integrated management over the long term. The enhanced resilience of these systems to drought, coupled with their ability to maintain comparable vine performance and grape quality under warmer climatic conditions, underscores their relevance in the face of increasing climate variability. As viticultural regions experience more frequent and intense heat and water stress events, the adoption of organic and biodynamic practices may contribute to enhanced long-term stability and sustainability in grape production.

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Authors' contributions Conceptualization: J.D., R.K.; methodology: J.D., R.K.; software: M.H.; formal analysis: J.D., K.S.; investigation: J.D., K.S., Y.W., G.M., M.F., M.S.; resources: M.H., M.S.; data curation: J.D., K.S.; writing—original draft preparation: J.D., K.S.; writing—review and editing: J.D., K.S., Y.W., G.M., M.F., M.S., M.H., R.K.; visualization: K.S.; supervision: J.D., R.K.; funding acquisition: M.S.

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Data availability All data supporting the findings of this study are publicly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.15478631>. The dataset includes data and metadata from the full 18-year InBioDyn field trial.

Code availability Not applicable. No custom code or software was generated or used during this study.

Declarations

Ethics approval This study involved plant material and did not require ethical approval according to institutional or national guidelines.

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interests K.S. reports financial support received from the German Viticulture Research Association during the conduct of this study. G.M. reports financial support received from the Software AG Foundation during the conduct of this study. J.D. reports financial support received from the German Viticulture Research Association and the Software AG Foundation during the conduct of this study. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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