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Is English viticulture carbon-negative? A pre-registered Life Cycle Assessment of 40 vineyards with carbon stock modelling

The rapid expansion of English viticulture may sequester carbon. Grapevines (*Vitis vinifera*) store more atmospheric carbon in woody biomass than annual crops, and their land cover can allow soil organic carbon (SOC) to accumulate. The overall greenhouse gas balance of English viticulture, however, remains unknown.

Using pre-registered methodology, I sampled 40 vineyards to conduct the first cradle-to-farm-gate life cycle assessment (LCA) of English wine grapes and their carbon footprint. Biological carbon sequestration was modelled under IPCC (2019) Tier 1 stock change models. Rejecting my main hypothesis, I show that average GWP100 (Global Warming Potential over 100 yrs.) was +0.255 kg CO₂-eq kg⁻¹ grapes (n = 40, SE = 0.0840), indicating that English vineyards are, on average, net carbon emitters. However, I found thirteen vineyards were net-negative, 12 of which were established on conventional cropland (cropland mean -0.192, n = 15, SE = 0.0745). In contrast, vineyards converted from pasture (+0.572, n = 12, SE = 0.142) and long-established vineyards (>20 years; +0.478, n = 13, SE = 0.122) were net emitters, suggesting limits to the potential and duration of vineyard carbon sequestration.

Land-use-history explained 44% of between-site GWP100 variance, with arable-dominated eastern counties showing the lowest mean emissions. Operational emissions were similar across groups; differences in GWP100 arose from biomass and SOC stock changes. My results show that viticulture in England has the potential to be carbon-negative, and that land-use history is critical; prioritising the establishment of vineyards on conventional cropland could unlock the sector's potential for carbon abatement.

Keywords: Life cycle assessment; viticulture; soil organic carbon; land use change; GWP100; English wine; carbon sequestration; carbon-negative food; climate change mitigation.

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1. Introduction

1.1 English viticulture is expanding rapidly, but its carbon balance is unquantified

Whether the rapid expansion of English viticulture represents a net carbon source or sink remains unknown. Life cycle assessments (LCAs) of viticulture across major wine-producing regions report carbon footprints ranging from 0.09 to 0.85 kg CO₂-eq kg⁻¹ grapes (Silva & Silva, 2022; Ferrara & De Feo, 2018; Litskas et al., 2020; Litskas et al., 2017; Poore & Nemecek, 2018; Steenwerth et al., 2015). While this variation partly reflects differences in vineyard management, it is also driven by inconsistent system boundary definitions during LCA design, particularly in the treatment of biological carbon stocks and land-use change (LUC) (da Silva & da Silva, 2022; Ferrara & De Feo, 2018). Many LCAs exclude LUC or apply static biological carbon factors (Bosco et al., 2013), implicitly assuming that established vineyards are near carbon equilibrium. This assumption is broadly defensible in long-established regions such as Bordeaux or Tuscany but is far less appropriate for a sector that has only recently emerged.

English viticulture represents such a case. The area planted with the common grapevine, *Vitis vinifera*, in England expanded more than sixfold between 2004 and 2025, from 761 ha to 4,841 ha (WineGB, 2025). Climatic and economic forces drive this expansion: warming growing seasons have extended suitability across southern England (Nesbitt et al., 2016, 2018, 2022), while international quality recognition (Sagues, 2018; WineGB, 2025) and sustained investment have accelerated establishment (Mercer, 2019). Declining viticultural suitability in traditional Mediterranean and Atlantic regions has further reinforced this northward shift (Santos et al., 2020; Van Leeuwen et al., 2024).

Continued expansion could make viticulture a non-trivial share of national agricultural land use. In France, Spain and Italy, vines account for approximately 3–6% of total utilised agricultural area (UAA) (Eurostat, 2022). In England, 3% of UAA would be approximately 267,000 ha, more than 55 times the current planted area (DEFRA, 2025), which would have substantial implications for national carbon accounting. Vineyard establishment replaces a mosaic of prior land covers, including arable cropland, permanent pasture, and semi-natural habitats. Because these land covers hold contrasting biological carbon stocks, vineyard expansion may function either as a carbon sink or a source, depending on prior land use.

To date, no LCA has quantified the carbon footprint of English grape production or assessed the net effect of associated land-use change on national soil and biomass carbon stocks (Bosco et al., 2013; Silva & Silva, 2022). This is a striking omission now that English viticulture is one of the most rapidly expanding perennial cropping systems in northern Europe (Nesbitt et al., 2018; WineGB, 2025). Moreover, perennial land-use transitions have been identified in UK and international climate strategies as credible mechanisms for agricultural carbon mitigation (CCC, 2020; Dimpleby, 2021; IPCC, 2019b). However, these strategies primarily frame perennial transitions as agroforestry, energy crops and woodland establishment, leaving perennial food systems such as vineyards, orchards and soft fruit as an empirically untested extension of this mitigation logic (Chenu et al., 2019; IPCC, 2019b; Sykes et al., 2020).

To date, no nationally representative LCA has examined the carbon-negative potential of an expanding English perennial food crop by incorporating biological carbon stock changes as well as operational emissions. Assessing the carbon effect of vineyard expansion requires an accounting framework that captures gains and losses across the two principal biological carbon pools: plant biomass and soil organic carbon (SOC).

1.2 Perennial cropping accumulates carbon in two biological pools: biomass and soil

Unlike annual systems, perennial crops retain much of the biomass produced through photosynthesis across multiple growing seasons, thereby prolonging the residence time of carbon (Brunori et al., 2016; Sanderman et al., 2017; Santos et al., 2020). Biomass, however, is a finite and dynamic store, subject to losses through senescence, disease, and management (e.g., pruning), and approaches equilibrium as plants mature, limiting the amount of carbon that can be stored in this pool in vineyards over time.

Soil organic carbon (SOC), derived from plant inputs, including residues, root turnover, and rhizodeposition, can form a stable long-term carbon pool. These inputs sustain microbial communities that regulate carbon retention. During decomposition and mineralisation, plant-derived carbon is partly respired as CO₂ (or CH₄ under anaerobic conditions) and partly incorporated into microbial biomass (Cotrufo et al., 2013; Kallenbach et al., 2016; Six et al., 2002; Sykes et al., 2020). Following microbial death, this carbon forms necromass, which can bind to clay minerals and metal oxides as mineral-associated organic matter (MAOM), the most stable SOC

fraction. Stability is further enhanced by physical protection within soil aggregates (Six et al., 2002). Despite this, SOC remains dynamic.

SOC pools are subject to losses from leaching, erosion, and soil disturbance; as a result, its persistence depends strongly on management, as shown in Fig. 1. Practices that maintain ground cover and minimise disturbance promote retention, whereas those that reduce inputs or disturb soil structure accelerate losses (Payen et al., 2021; Sykes et al., 2020). Like biomass, SOC sequestration is finite: stocks approach saturation as inputs and losses equilibrate, and accumulated gains are vulnerable to changes in management. Whether vineyard establishment builds or depletes these carbon stores depends heavily on prior land use.

1.3 Prior land use determines if vineyard conversion leads to carbon gains or losses

Conversion of land into vineyards has different effects on SOC stocks. Conventionally managed arable soils are typically depleted in SOC due to prolonged tillage, limited root inputs, and structural disruption. This depletion reflects a legacy of agricultural expansion and intensification that has been associated with carbon losses (Sanderman et al., 2017). In this context, vineyard establishment partially reinstates the ecological processes that sustain carbon stocks in natural systems. Under appropriate management, vineyard land cover can provide continuous below-ground inputs, reduced tillage disturbance, and persistent above-ground biomass accumulation. As demonstrated in Fig. 1, these changes lead to a partial recovery of SOC from the carbon-depleted state of conventional arable cultivation.

In contrast, permanent pastures that are carefully managed, receive few inorganic inputs, and are not severely degraded can maintain high SOC through continuous root turnover, manure deposition, and minimal soil disturbance. Conversion to vineyard might therefore reduce carbon stocks by disturbing a system with potentially high baseline SOC. These contrasting trajectories, and the net carbon balance they produce, can only be quantified within a framework that explicitly captures dynamic carbon stock changes arising from land-use history alongside production emissions.

1.4 Life Cycle Assessment can capture both emissions and sequestration

LCA is the internationally standardised framework (ISO, 2006a, 2006b) for quantifying the environmental impacts of a product across its production chain. Applied at the cradle-to-farm-gate boundary, an LCA can capture greenhouse gas emissions from vineyard establishment and operation, including fuel combustion, agrochemical manufacture, infrastructure, and soil N₂O emissions. This study's system boundary includes biomass and SOC stock changes, with emissions and removals aggregated using IPCC AR6 GWP100 (100-year Global Warming Potential). This approach enables evaluation of whether English vineyards act as net emitters or sinks under active land-use change.

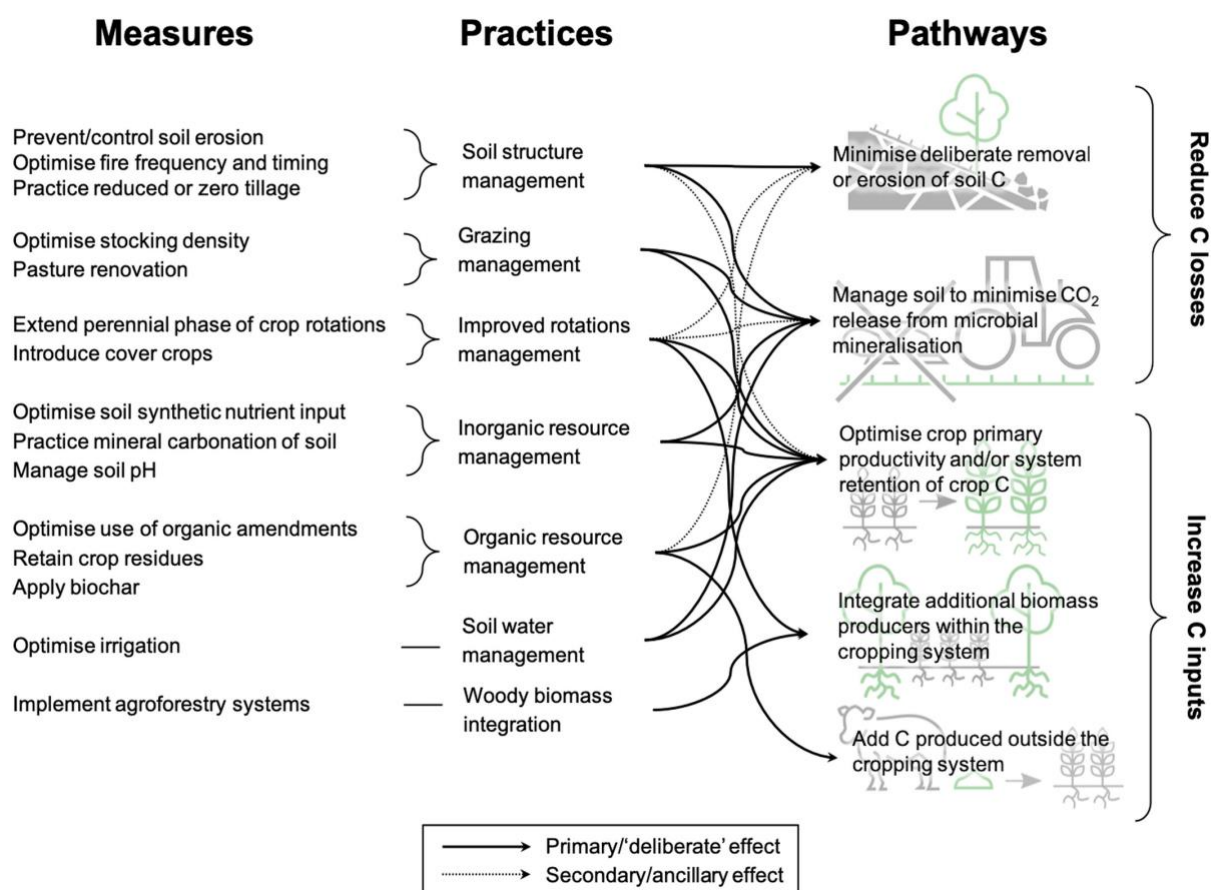


Figure 1. Shortlist of land management measures with the highest potential for SOC sequestration and pathways to SOC sequestration. Adapted from Figure 2 in Sykes et al. (2020).

2. Research objectives

I present the first nationally representative LCA of English viticulture to evaluate whether vineyards, established under England's current land-use change context, can achieve net-negative carbon balances. I address four objectives, distinguishing pre-registered from exploratory work.

2.1 Quantify whether English wine grapes are carbon-negative (pre-registered).

I test my primary pre-registered alternative hypothesis that the mean GWP100 of English wine grapes is significantly negative.

$$H_1: \text{mean GWP100} < 0$$

2.2 Assess the effect of land-use history on carbon footprint (further analysis).

I assess whether GWP100 values differ between established vineyards (>20yrs.) and recently converted vineyards (<20yrs.) in a binary analysis. I further assess whether GWP100 varies across three land-use categories: former conventional cropland, former pasture, and established vineyards (>20 years since establishment; no recent land-use change). Although not pre-registered, H_2 was specified before statistical analysis based on the mechanism in section 1.3 and is reported alongside robustness checks.

Let μ_C , μ_P , and μ_E denote the mean GWP100 of cropland-converted, pasture-converted, and established vineyards, respectively. The ordering assumes biomass sequestration in pasture-converted vineyards offsets pasture SOC losses on a per-kg basis, a prediction the contribution analysis (Objective 3) tests.

$$H_2: \mu_C < 0 < \mu_P < \mu_E$$

2.3 Identify the primary sources of emission and sequestration in English viticulture (pre-registered contribution analysis).

As planned in pre-registration, I quantify the dominant operational emission sources and biological sequestration pools and assess variation by prior land use. No directional predictions were pre-registered. Based on the broader agricultural LCA literature, I expected that fuel use, agrochemical inputs, and infrastructure are the principal contributors to emissions across all site types, while SOC is the predominant driver in sequestration dynamics over biomass.

2.4 Describe regional trends in English viticulture's carbon footprints (Exploratory).

I describe spatial variation in GWP100 as an exploratory, hypothesis-generating analysis. Consistent with Objectives 1–2, I expected that regions with a higher proportion of former arable land are more likely to exhibit net-negative carbon balances, reflecting greater potential for soil carbon sequestration following conversion.

3. Methods and Materials

3.1 Materials

3.1.1 The HESTIA Platform

I produced Life Cycle Impact Assessments (LCIAs) using HESTIA (HESTIA, 2025), an open-source University of Oxford platform for structuring agricultural life cycle inventories (LCIs) and calculating environmental impacts. HESTIA standardises inventory data on inputs, outputs, land-use history, soil management and infrastructure, and applies pre-validated models from the IPCC (IPCC, 2019a) and peer-reviewed literature (Tables S1 and S2). HESTIA's open-access and transparent structure improves methodological consistency and reproducibility compared with many LCA modelling approaches. Carbon footprints are reported using IPCC AR6 100-year factor (GWP100), expressed as kg CO₂-eq kg⁻¹ of wine grapes (primary functional unit) and kg CO₂-eq ha⁻¹ of vineyard land (secondary). A GWP100 metric was chosen to align with UK Net Zero accounting outputs (CCC, 2020) and the relevant policy framework. GWP20 over-weights short-lived gases, which are minor contributors in vineyard systems dominated by N₂O and CO₂. GWP* (Cain et al., 2019) though more accurate for short term and long term GHG stock-flow, is not yet standardised in agricultural LCA nor in HESTIA.

3.1.2 IPCC Tier 1 Soil Organic Carbon Model and Biomass models

I modelled SOC stock changes using the IPCC (2019) Tier 1 method (HESTIA, 2025; IPCC, 2019a), within HESTIA. Tier 1 is a standardised, globally applicable approach that estimates SOC changes based on land use, land-use change (LUC), prior land management/practice, climate zone, and soil type inputs, without requiring direct soil sampling data. This method abstracts the biological processes described in Section 1.2, capturing their net effect through empirically calibrated stock-change factors, estimating SOC outcomes for given combinations of the following equation's factors. This abstraction is the source of both the method's tractability and its principal limitation, addressed in Section 5.7. The method calculates each year's SOC equilibrium through the following equation using peer-reviewed IPCC factors.

$$SOC_{eq} = SOC_{ref} * FLU * FMG * FCI$$

Where SOC_{ref} is the IPCC reference mineral-soil stock and FLU , FMG , FCI are dimensionless stock-change factors for land use, management regime and carbon inputs respectively (all kg C ha⁻¹).

Starting from the earliest year in the inventory, HESTIA interpolates between SO_{eq} values following changes in land-use/management for each subsequent year. In line with the IPCC (2019) Tier 1 methodology, SOC changes are assumed to cease after 20 years of stable land use and management, on the basis that the system has reached SO_{eq} . A limitation of the Tier 1 approach is that it does not allow management changes in tillage or carbon input to affect SOC in permanent crop systems. This restricted the analysis to modelling SOC changes driven by land-use change alone; management effects on SOC within vineyards could not be captured. I selected Tier 1 because Tier 2 modelling requires multi-year inventory records, and similarly, direct SOC sampling requires soil measurements over multiple years - neither was feasible within this study's timeframe.

I modelled above- and below-ground biomass carbon stocks using the IPCC (2019) Tier 1 Gain-Loss method (IPCC, 2019), applied to perennial woody cropland and implemented within HESTIA. HESTIA's implementation includes vineyard-specific parameters to increase the precision of the model. For each site, the model uses a climate-zone- and crop-specific above-ground biomass equilibrium value (kg C ha^{-1}) from IPCC (2019) and converts it to a below-ground stock using the corresponding root-to-shoot ratio. The model assumes linear accumulation towards that equilibrium over 20 years following land-use change.

$$\Delta C_{B,t} = \frac{B_{AG,eq} * (1 + R)}{T_{eq}} \quad \text{for } 0 < t \leq T_{eq}$$

$$\Delta C_{B,t} = 0 \quad \text{for } t > T_{eq}$$

Where $B_{AG,eq}$ is the climate- and crop-specific biomass equilibrium (kg C ha^{-1} ; IPCC, 2019a), R the below-to-above-ground ratio, T_{eq} is 20 years, and $\Delta C_{B,t}$ the annual biomass-stock change. After 20 years biomass pools are assumed at steady state matching the SOC interpolation cut-off.

3.1.3 Primary and Secondary Data Sources

From October 2025 to February 2026, I collected primary data on the 2024–2025 harvest cycle via interviews with vineyard managers (20 in-person, 20 online). I designed a standardised questionnaire to capture agricultural inputs, management practices, yields, land area, LUC history, soil measurements and soil management, enabling consistent LCI construction across sites. To identify and contact eligible vineyards, I consulted three national databases: WineGB (Wine GB,

2025), the Great British Vineyard Guide (The Great British Vineyard Guide, 2025), and the English Wine Vineyard Database (English Wine Vineyard Database, 2025). These sources provided estimates for vineyards' geographic distribution, areas, production volumes, and contact details used to construct the sampling frame.

3.2 Methods

3.2.1 Pre-Registration and Power Analysis

I pre-registered this study on Open Science Framework (osf.io/9v2ah) before full-scale data collection and analysis, ensuring transparency and preventing post-hoc hypothesis revision. To determine the minimum sample size required to test the primary hypothesis, an a priori power analysis was conducted using G*Power 3.1 (Faul et al., 2007). A target standardised effect size of Cohen's $d \approx 0.40$ was specified, corresponding to a minimum detectable mean of $-0.42 \text{ kg CO}_2\text{-eq kg}^{-1}$ grapes relative to a baseline of zero (carbon neutrality), using the population standard deviation of $1.05 \text{ kg CO}_2\text{-eq kg}^{-1}$ for vineyard GWP100 reported by Poore & Nemecek (2018). This magnitude represents a meaningful shift into carbon-negative production, not a trivial deviation from zero. Assuming a significance level of $\alpha = 0.05$ and a statistical power of 0.80, the analysis indicated that a minimum sample size of 40 vineyards was required for a one-sample, one-tailed t-test. This sample size is feasible given that England hosts over 1,000 registered commercial vineyards, requiring a response rate of less than 4%.

3.2.2 Stratified Sampling and Recruitment

Following my pre-registration, I employed a stratified sampling approach to ensure representative coverage of England's wine-producing regions. I stratified by the 8 most productive wine-growing counties: Kent (1239ha), East and West Sussex (1132ha), Essex (469ha), Hampshire (426ha), Norfolk and Suffolk (400ha) and Surrey (130ha) (English Wine Vineyard Database, 2025; The Great British Vineyard Guide, 2025; Wine GB, 2025). Counties with three or more active commercial vineyards but falling outside these groups were retained as a single "other regions" stratum, from which one or two vineyards were sampled to capture geographic and viticultural variation beyond the principal producing areas. Counties with fewer than three active vineyards were excluded on the basis that they do not contribute meaningfully to national production. Within each county stratum, vineyards were further stratified by production scale into three categories: small ($<2 \text{ ha}$ or $<10,000$ vines),

medium (2–10 ha or 10,000–50,000 vines), and large (>10 ha or >50,000 vines). A target sample of 40 vineyards was set, with quotas allocated proportionally to each county's share of national planted area and, within counties, distributed across the three size categories in approximate proportion to their representation in the WineGB vineyard database. Vineyards within each stratum cell were selected by simple random sampling from the database.

One Oxfordshire-based vineyard was recruited during a pilot phase to test questionnaire effectiveness. Its data was included in the final analysis following confirmation that the questionnaire required no structural revision. Subsequently, I contacted eligible vineyard managers and owners by email to invite them to participate. Non-respondents received a follow-up email after one week. To incentivise participation, I offered all participating vineyards a personalised, anonymised, complimentary LCA of their agricultural practices. Contact was also made with WineGB and relevant industry networks to encourage participation from larger producers. Informed consent was obtained from all participants prior to data collection, in accordance with the University of Oxford CUREC ethical review process, which was applied for and granted under CUREC number: 1145449.

3.2.3 Questionnaire Design and LCI Construction

I administered a structured questionnaire to each participating vineyard manager, conducted either in-person or via online meeting, each interview taking ~90 minutes. The questionnaire was divided into four sections covering: vineyard demography (age, layout, replantation rate), vineyard operations (inputs, practices, yields, infrastructure), winery operations (pressing, cleaning, bottling, packaging, energy use), soil measurements and land use data (LUC history, SOC measurements where available). The winery section of this questionnaire was fulfilled by 13 wineries, which represent valuable data for future analysis, but is not included here.

I structured each site's data to conform to the HESTIA glossary and schema, a process that produced a dataset of 1299 columns × 40 rows, capturing agrochemical inputs, infrastructure specifications, fuel quantities, yield data, management practices, land-use histories, and soil measurements. Where vineyards contained juvenile sections not yet at full productive capacity, I calculated their yield per hectare of mature vines as a proxy for full-maturity output, ensuring comparability across sites at different stages of establishment. Following this HESTIA upload, a full LCIA was run for each

site, generating several environmental impact indicators, and the focus indicator of this study, site-level GWP100 and emission sources.

3.2.4 Statistical Analysis

I performed all statistical analyses in R (v4.4.2). To test whether English wine grapes are carbon-negative at the sector level, I conducted a one-sample, two-tailed *t*-test of mean GWP100 against zero (a deviation from the pre-registered one-tailed test, noted below). Normality of GWP100 values was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots and histograms; the *t*-test is robust to mild departures from normality at this sample size. Following the pre-registered outlier protocol, I flagged potential outliers as values more than three SDs from the mean and checked for plausibility against input data. Two sites met the criterion: _0030gv (GWP100 = +1.86 kg CO₂-eq kg⁻¹) and _0014gv (−1.03 kg CO₂-eq kg⁻¹). Both were retained as their values were plausible given their land-use histories and consistent with IPCC Tier 1 predictions. Leave-one-out sensitivity analysis (Section 4.2.3) confirmed that removing either site preserved the direction of group-level results.

To test the effect of land-use history, I ran two analyses: (i) an independent-samples *t*-test comparing GWP100 between vineyards that had undergone land-use change in the preceding 20 years and those that had not, and (ii) a one-way ANOVA across three prior land-use categories (cropland, pasture, established vineyard - the latter being the grouping above that had not undergone recent land use change as indicated by identical colouration in Fig. 2 b, c and d). Tukey HSD identified pairwise differences for significant ANOVA results, and group means were tested against zero to assess carbon negativity at the subgroup level. ANOVA is robust to mild departures from normality at these subgroup sizes ($n = 12\text{--}15$), and furthermore, all parametric results were confirmed by a distribution-free permutation test (Section 4.2.3) with identical conclusions. Production-scale effects were tested by ANOVA across three size categories (small <2 ha, medium 2–10 ha, large >10 ha). HESTIA's impact-assessment output was decomposed into source and sink contributions to identify dominant emission and sequestration pathways across the full sample and by prior land-use group. Additionally, regional variation was visualised on two choropleth maps with county-level data aggregated into regional groups (minimum $n = 3$; nearest-neighbour merging for under-sized counties). Fig. 5a shows averaged GWP100 by region, Fig. 5b shows the proportion

of utilised agricultural area under pasture and cropland. Given small and uneven regional sample sizes, this analysis was treated as exploratory rather than inferential.

Three deviations from the pre-registered protocol are noted for transparency. (i) The pre-registered one-tailed t -test was applied as a two-tailed test for the primary analysis, upon preliminary inspection that the effect direction was uncertain. The 95% confidence interval (Section 4.1.2) excludes zero, demonstrating statistical detectability under the more conservative test. (ii) The categorical land-use hypothesis (H_2) was specified post-pre-registration but pre-data-analysis, based on the IPCC Tier 1 mechanistic framework. (iii) Secondary environmental indicators and the 75cl bottle functional unit listed in the pre-registration were not analysed here owing to scope constraints and winery data limitations and are reserved for future work.

4. Results

4.1 Raw data suitability and mean GWP100

4.1.1 Sample conformity

The achieved sample met the pre-registered target of 40 vineyards and exceeded the pre-registered design in two respects. First, the stratification across counties and production scales was well-realised: all eight principal wine-producing counties were represented, and the three vineyard size categories (less than 2 ha, between 2 and 10 ha and greater than 10 ha) were populated across the sample, producing a dataset with geographic and operational coverage. Second, the effect size observed was greater than assumed in pre-registered power analysis, achieving ample power to test hypothesis 1. The Shapiro–Wilk test indicated that total GWP100 values were approximately normally distributed ($W = 0.97$, $p = 0.357$; Fig. 2a violin) conforming to the assumptions of a one-sample t -test.

4.1.2 Net GWP100 across all sites

The mean GWP100 across all 40 sites was $+0.255 \text{ kg CO}_2\text{-eq kg}^{-1} \text{ grape}$ (Fig. 2a, $SD = 0.531$; 95% CI: $+0.088$ to $+0.422$; $t(39) = 3.04$, $p = 0.004$, two-tailed one-sample t -test), providing no support for pre-registered H_1 that English viticulture is carbon-negative at the sector level. However, 13 of 40 sites (32.5%) achieved net-negative carbon balances ($GWP100 < 0$). The standard deviation was large relative to mean, indicating substantial between-site heterogeneity, explored in section 4.2.

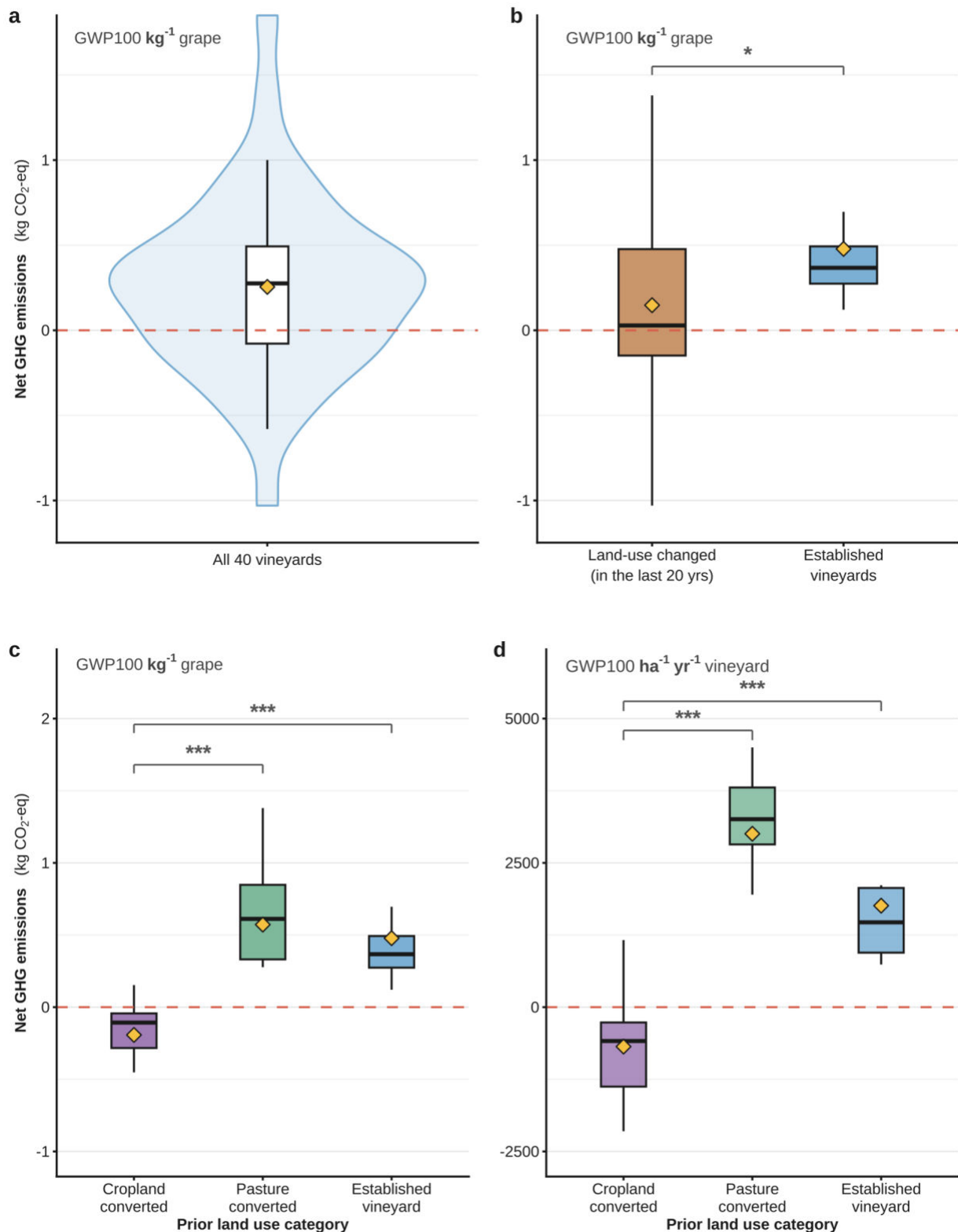


Figure 2. GWP100 distribution of English vineyard grape production. (a) Violin and box plot of GWP100 across all 40 vineyards (kg CO₂-eq kg⁻¹ wine grape, GWP100). (b) GWP100 by binary land-use change status (established vineyards vs recently converted, < 20 yr). (c) GWP100 kg⁻¹ grape by prior land-use category. (d) GWP100 ha⁻¹ yr⁻¹ by prior land-use category. Amber diamonds (◆) represent group mean. Red dashed line (---) represents carbon neutrality. Boxplots display median ± IQR and whiskers are 1.5 × IQR. Significance brackets are Tukey adjusted HSD (***) $p < 0.001$; (*) $p < 0.05$; ns $p \geq 0.05$).

4.2 Effect of prior land use on GWP100

4.2.1 Recency of land-use change

Vineyards that had undergone land-use change less than 20 years ago ($n = 27$) had a wider and more variable distribution of GWP100 values than those that had not ($n = 13$; Welch $t = 2.06$, $p = 0.049$; Fig. 2b), though this difference was only marginally significant. No established vineyard site achieved a carbon-negative balance, due to the nature of IPCC Tier 1 modelling, whereas 13 of 27 recently converted sites did. This binary classification masks further opposing responses by prior land-use.

4.2.2 Prior land-use category

Prior land use category was the dominant predictor of GWP100, explaining 44% of between-site variance (one-way ANOVA: $F(2,37) = 14.67$, $p < 0.001$, $R^2 = 0.44$; Figs. 2c–2d). Cropland-converted vineyards were net carbon sinks (mean = $-0.192 \text{ kg CO}_2\text{-eq kg}^{-1}$ grapes; Tukey-adjusted $p < 0.001$ vs both other groups), while pasture-converted (mean = $+0.572 \text{ kg CO}_2\text{-eq kg}^{-1}$ grapes) and long-established vineyard sites (mean = $+0.478 \text{ kg CO}_2\text{-eq kg}^{-1}$ grapes) were net sources. The predicted rank ordering of pasture and established vineyard groups was not supported, as both were net sources and statistically indistinguishable. Means tested against zero confirmed that the cropland group mean was significantly negative ($p = 0.006$, one-tailed), while pasture and vineyard groups were significantly positive. Twelve of the 13 carbon-negative sites were cropland-converted. The single non-cropland carbon-negative site was a pasture conversion classified as 'severely degraded', a category that sequestered carbon when modelled (unlike 'nominally managed', which applied to all other pasture sites). Vineyard size was not substantively meaningful to GWP100, showing a modest association ($F(2,37) = 3.43$, $p = 0.043$, $R^2 = 0.16$, Fig. S1), although post-hoc tests suggested this was limited to a difference between small and medium vineyards, with no significant difference involving large vineyards.

4.2.3 Robustness checks

Four additional analyses confirmed the robustness of the land-use effect. First, median GWP100 values were consistent with group means (mean-median divergence < 0.5 SD in all groups). Minimal divergence indicates that outliers were not unduly influencing central tendency. Second, bootstrap 95% confidence intervals (10,000 resamples, seed = 42) excluded zero for all three land-use groups

(Fig. S2), confirming directional robustness under resampling. Third, a leave-one-out analysis identified two influential sites, _0014gv (Cropland; GWP100 = $-1.03 \text{ kg CO}_2\text{-eq kg}^{-1}$; 31% shift on removal) and _0030gv (Vineyard; GWP100 = $+1.86 \text{ kg CO}_2\text{-eq kg}^{-1}$; 24% shift), but both removals preserved the direction of the group result, confirming the land-use effect is not dependent on any single observation. Fourth, a permutation test (10,000 permutations) confirmed that between-group differences were significant independently of normality (observed $F = 14.667$; permutation $p < 0.0001$). The land-use effect remained significant after controlling for vineyard size ($p < 0.001$) and county, confirming that neither variable affects the primary result.

4.3 Emission and carbon sequestration sources

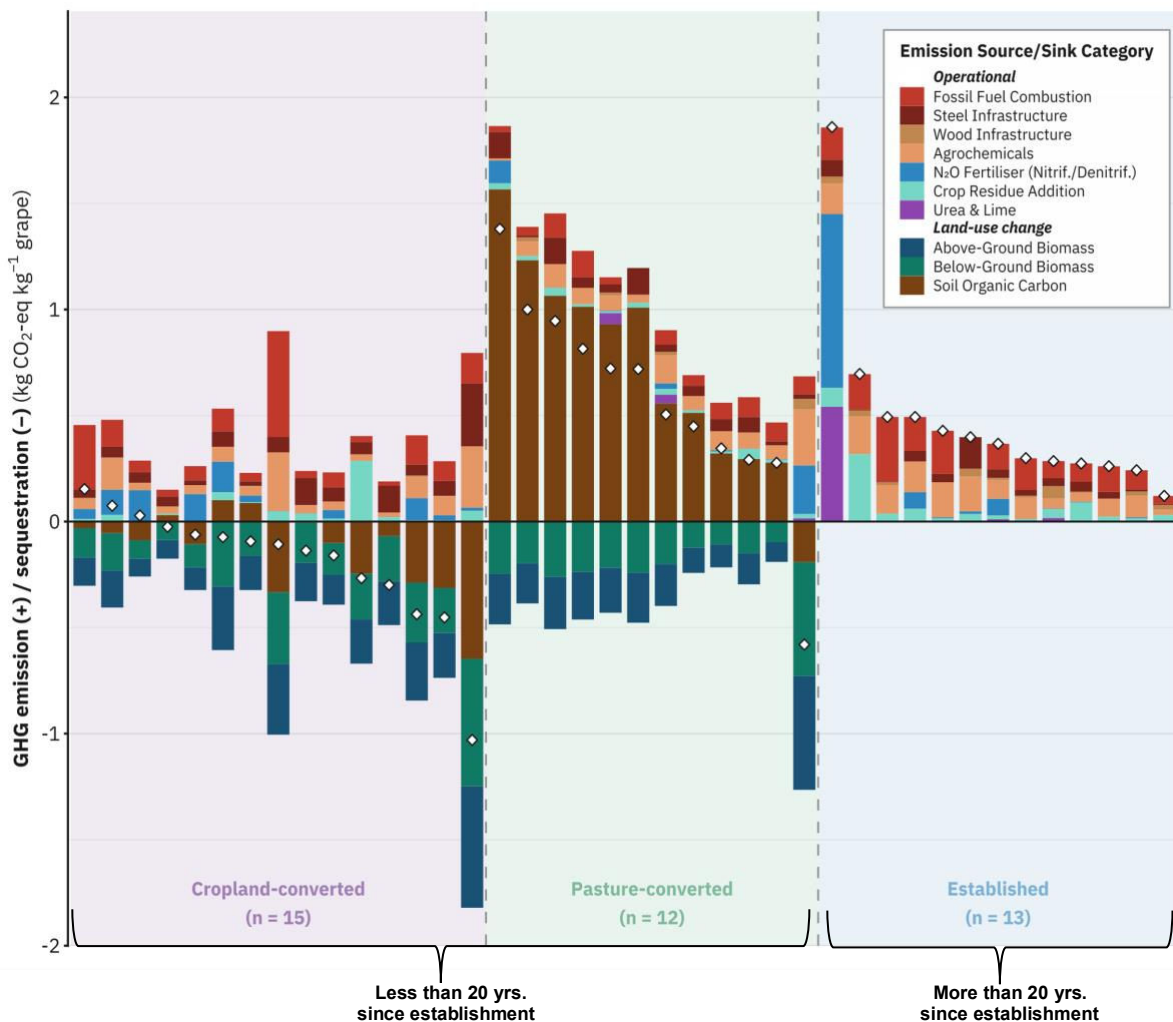


Figure 3. Per-vineyard GHG emission and sequestration source by prior land-use category. Stacked bars show the contribution of ten GHG source/sink categories to the GWP100 of each vineyard ($n = 40$), grouped by prior land use, separated by dashed lines. Sites descend by net GWP100. Bars above zero represent GHG sources, bars below zero represent carbon sinks. The SOC stock change and biomass terms are absent in vineyards more than 20 yrs. old, reflecting the IPCC Tier 1 carbon stocks modelling. White hollow diamonds (◇) report site-level net GWP100 ($\text{kg CO}_2\text{-eq kg}^{-1}$ wine grape).

4.3.1 SOC stock change: the primary driver of between-group variation

SOC stock change was the single largest process-domain term by absolute magnitude (overall mean = $+0.163 \text{ kg CO}_2\text{-eq kg}^{-1}$; Table S3, Fig. 4 and Fig. S4) and was the primary mechanistic driver of between-group differences in net GWP100. For cropland-converted sites, mean SOC change, modelled under IPCC Tier 1, was $-0.137 \text{ kg CO}_2\text{-eq kg}^{-1}$ ($-552 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) - a net sink. Although the cropland-converted group was a net SOC sink, four cropland-converted sites showed neutral or modestly positive SOC stock changes (Fig. 3, Fig. S4). In each case, this difference is explicable from the management history declared at interview (prior rotation patterns, short fallow periods and 4-year set-asides) that caused different SOC trends to be modelled. For pasture-converted sites, the mean SOC term was $+0.715 \text{ kg CO}_2\text{-eq kg}^{-1}$ ($+3735 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), a large source, reflecting SOC loss from high-carbon permanent grassland soils. For established vineyard sites, SOC stock change was zero under the 20-year IPCC equilibrium assumption. The difference in the SOC term alone between cropland and pasture conversion was $4287 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, which exceeds total operational emissions and is larger than the full net GWP100 difference between groups ($3846 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$).

4.3.2 Biomass sequestration

Above-ground (AGB) and below-ground (BGB) biomass stock changes were substantial and near-identical across both converted groups: AGB = -0.212 vs $-0.213 \text{ kg CO}_2\text{-eq kg}^{-1}$, BGB = -0.218 vs $-0.218 \text{ kg CO}_2\text{-eq kg}^{-1}$ (cropland vs pasture). Per-hectare values were similarly matched (AGB: -1004 vs -993 , BGB: -1030 vs $-1018 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$). This near identity is methodological and expected: IPCC Tier 1 applies the same biomass accumulation rates to all conversions to perennial crops irrespective of prior land cover. So AGB/BGB differences are not informative about prior land use under this framework.

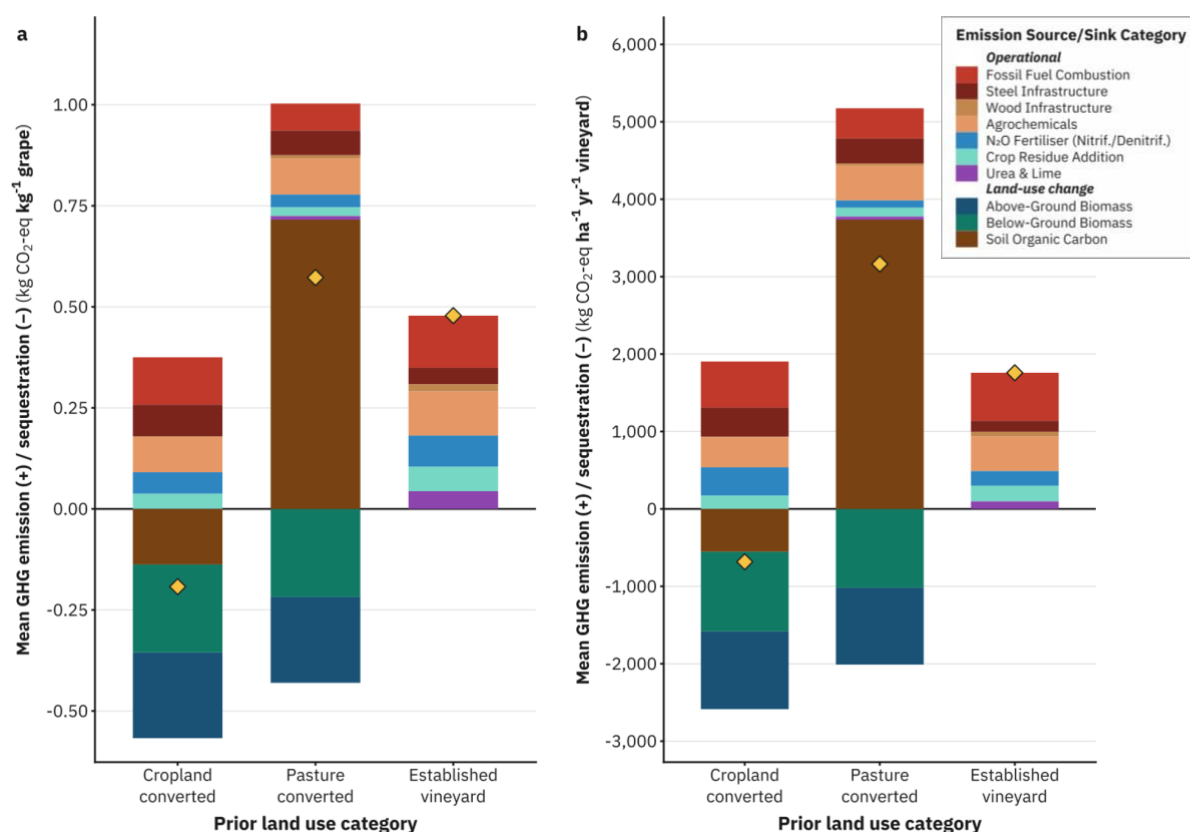


Figure 4. Mean GHG emission sources per prior land-use category. (a) Mean GHG contribution by emission source category per prior land-use group (kg CO₂-eq kg⁻¹ grape). (b) Equivalent per-hectare analysis (kg CO₂-eq ha⁻¹ yr⁻¹). Individual site GWP100 values overlaid as black points. Bars above zero = net GHG emissions; bars below zero = net carbon removal. SOC = soil organic carbon stock change. LUC = land-use change. Table S3 and S4 provides numerical breakdown of each category.

4.3.3 Operational emission sources

Summed operational emissions averaged +0.383 kg CO₂-eq kg⁻¹ overall (+1,718 kg CO₂-eq ha⁻¹ yr⁻¹), with per-hectare totals broadly comparable across groups (cropland: +1,905; pasture: +1,439; established vineyard: +1,569 kg CO₂-eq ha⁻¹ yr⁻¹; Tables S3, S4). Fossil fuel combustion was the largest operational source across all groups (overall mean = +0.106 kg CO₂-eq kg⁻¹, Fig. S3), reflecting mechanised spray applications, inter-row management, and harvest operations.

Agrochemicals, representing embedded Scope 2/3 GHG emissions from fertiliser, pesticide, herbicide, and machinery production, were the second-largest operational source (0.095 kg CO₂-eq kg⁻¹) and were broadly consistent across groups (0.088–0.109 kg CO₂-eq kg⁻¹; Table S3), making them the most tractable target for sector-wide mitigation independent of land-use history.

Steel infrastructure (trellis wires, posts, and fixings) contributed $0.061 \text{ kg CO}_2\text{-eq kg}^{-1}$ overall, comparable to N_2O fertiliser emissions ($0.055 \text{ kg CO}_2\text{-eq kg}^{-1}$) and larger than crop residue, urea, or wood infrastructure terms. Per-kg steel contributions ranged from $0.079 \text{ kg CO}_2\text{-eq kg}^{-1}$ in cropland-converted sites ($378 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) down to $0.041 \text{ kg CO}_2\text{-eq kg}^{-1}$ in established vineyards ($142 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$). This pattern reflects historical material choices: many established vineyards in the sample used creosoted wooden stakes, which were widely available before the EU Biocidal Products Regulation restricted creosote sale on public health grounds (EU, 2012). More recently established cropland- and pasture-converted sites have therefore adopted steel trellis systems, lifting their per-kg steel emission contributions.

N_2O from fertiliser application was highest in established vineyard sites ($0.077 \text{ kg CO}_2\text{-eq kg}^{-1}$), reflecting more intensive fertiliser management in mature systems. The lower per-kg fossil fuel value observed in pasture-converted sites (0.067 vs $0.117\text{--}0.129 \text{ kg CO}_2\text{-eq kg}^{-1}$ in other groups) reflects yield dilution rather than genuinely lower fuel use, a pattern confirmed by comparable per-hectare values across groups ($391\text{--}621 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$). Crop residue decomposition, urea and lime, and wood infrastructure (vine stakes) were minor contributors throughout (Tables S3 and S4).

4.4 Regional variation in GWP100

Regional mean GWP100 (Fig. 5a) was lowest in eastern England (Norfolk: -0.24 ± 0.07 , $n = 3$; Essex and Suffolk: -0.20 ± 0.59 , $n = 4$) and highest in southern and south-western regions (East Sussex: $+0.72 \pm 1.02$, $n = 3$; South West: $+0.59 \pm 0.49$, $n = 5$). Thames Valley and Kent showed intermediate positive values (0.26 and $0.20 \text{ kg CO}_2\text{-eq kg}^{-1}$; $n = 8$ each). Counties with the highest arable proportion (Norfolk and Suffolk: $\sim 72\%$; Fig. 5b) correspond to the lowest GWP100 means. Within-region SDs were large throughout. Given the small and uneven within-region sample sizes ($n = 3\text{--}8$), this analysis is treated as exploratory.

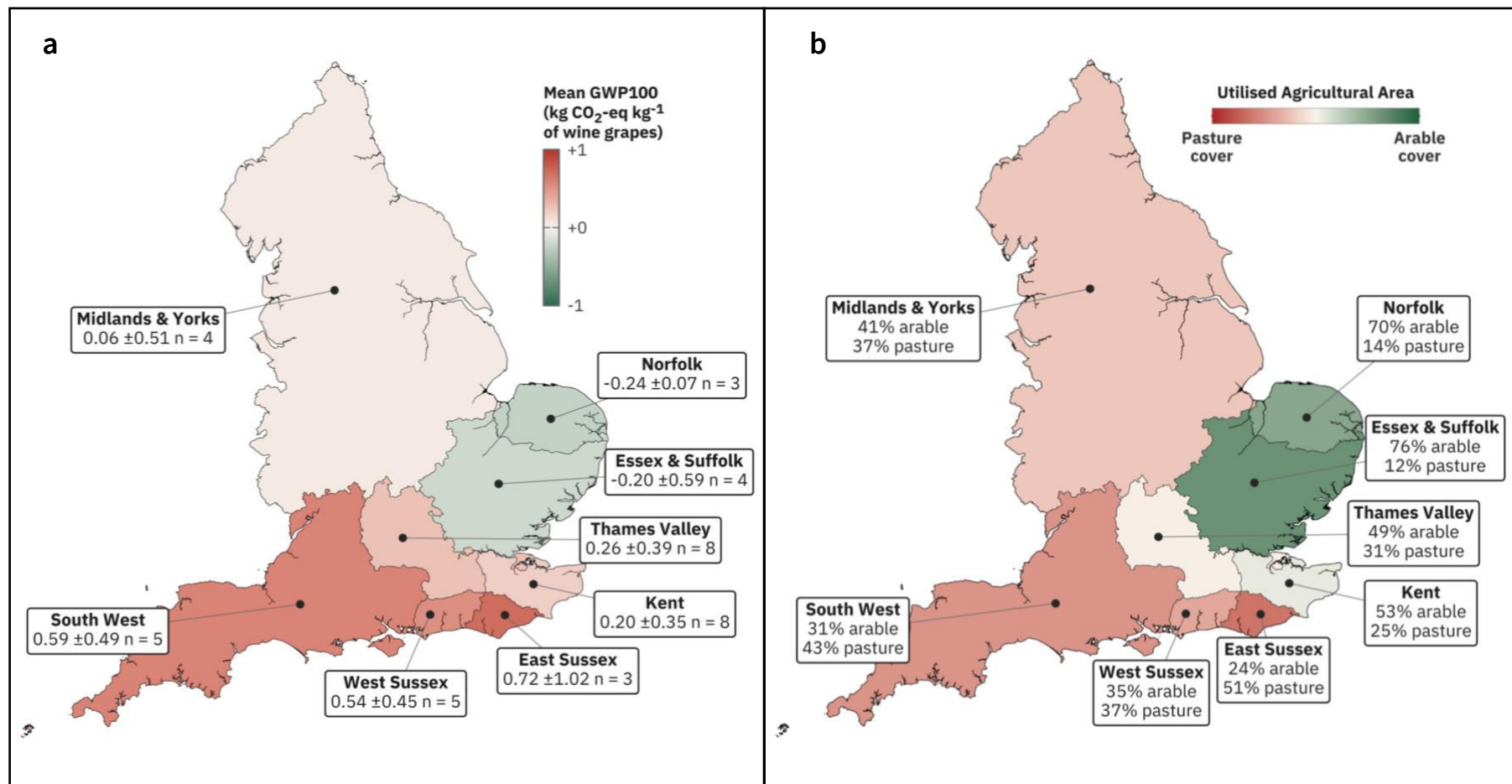


Figure 5. Regional variation in vineyard carbon footprint and agricultural land-use across England. (a) Choropleth map showing mean GWP100 (kg CO₂-eq kg⁻¹ grape) by regional group (minimum n = 3 per group, groups with fewer sites merged into the nearest geographic neighbour by cascade). Diverging colour scale: green represents net carbon sink, beige represents carbon-neutral, red represents net carbon source. (b) Choropleth map showing the proportion of utilised agricultural area (UAA) under arable crops by the same regional groupings as in (a), illustrating the agricultural land-use context of vineyard establishment. Over 50% arable cover is coloured in shades of green, while lower arable cover (and circumstantially pasture cover over 30%) is coloured in shades of red. Boundaries: ONS Open Geography Portal, May 2023. Land-use data: DEFRA June Survey of Agriculture & Horticulture 2025.

5. Discussion

5.1 A third of English vineyards are already carbon-negative, with prior land use determining which sites achieved it

While the sector mean proved positive ($+0.255 \text{ kg CO}_2\text{-eq kg}^{-1}$ wine grape; $p = 0.004$), about one-third (13/40) of vineyards were net carbon sinks, with GWP100 values as negative as $-1.03 \text{ kg CO}_2\text{-eq kg}^{-1}$. No single established vineyard without recent land-use change achieved carbon negativity, due to the modelling assumption that established vineyards have saturated biological carbon stores and therefore do not have capacity to sequester. These results establish that English viticulture has genuine but conditional carbon sequestration potential, and that the condition is largely determined by one upstream factor - the prior land use, which dictates SOC sequestration or emission potential. Even without high-resolution year-on-year management modelling, the strength of the land-use signal makes this an actionable finding for both vineyard establishment decisions and sector-wide policy.

5.2 The dominant role of SOC dynamics

SOC stock changes, modelled via IPCC (2019) Tier 1, were the dominant driver of between-group differences in GWP100. The sampled croplands were mostly conventionally managed (full tillage, low carbon inputs) and the pastures mostly nominally managed with high SOC stocks. Under Tier 1, depleted cropland soils accumulate carbon on conversion to a low-disturbance perennial system, generating a modelled SOC sink of $-552 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, enough, alongside biomass sequestration ($\approx -2034 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), to deliver net carbon negativity. High-SOC pasture soils, except the single severely degraded site, lose carbon when the sward is removed at planting, generating a modelled SOC source of $+3735 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. The $4,287 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ swing between cropland and pasture conversion exceeds the per-hectare operational total of any group (range: $1,439\text{--}1,905 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), and is more than double the overall operational mean of $1,718 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. Biomass sequestration in these pasture systems cannot match the SOC emission source.

Biomass sequestration ($\text{AGB} + \text{BGB} \approx -2034 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) is near-identical across cropland- and pasture-converted groups under Tier 1, so the entire between-group difference is attributable to SOC dynamics. This is consistent with Sanderman et al.'s (2017, corrected 2018) estimate of a 116

Pg C global soil carbon debt accumulated over 12,000 years of agricultural land use: cropland conversion to viticulture constitutes a localised partial repayment of that debt, while pasture conversion extends it (except where pasture is severely degraded and SOC already low). Pasture-converted and established vineyard sites had statistically indistinguishable carbon balances (Tukey $p = 0.89$), suggesting that once SOC reaches its modelled 20-year Tier 1 equilibrium, the carbon balance is determined entirely by operational emissions. The established vineyard mean (+0.478 kg CO₂-eq kg⁻¹) therefore represents the long-run steady state to which all recently converted vineyards are tending under the model. Carbon negativity in English viticulture is, on this evidence, a time-limited benefit of early establishment rather than a permanent property of the land use.

5.3 Dominant operational emissions match those found in global LCA literature, indicating shared mitigation pathways

Fossil fuel combustion and agrochemicals dominated operational emissions, consistent with Mediterranean viticulture LCAs and broader agricultural meta-analyses (Ferrara and De Feo, 2018; Litskas et al., 2017; Poore and Nemecek, 2018). Agrochemical contributions were broadly consistent across land-use groups (0.088–0.109 kg CO₂-eq kg⁻¹), making them the most tractable sector-wide target since their reduction is not confounded by land-use history. Steel infrastructure was comparable to N₂O fertiliser emissions and larger than crop residue, urea, or lime, a result rare in the viticulture LCA literature, where most studies omit infrastructure or aggregate it within capital goods. The creosoted-to-steel-post transition driven by UK biocide restrictions represents an underappreciated mitigation opportunity at the current pace of new planting, and warrants inclusion in future sector-level carbon accounting.

No combination of operational emission sources accounts for the between-group differences in net GWP100: without favourable modelled SOC dynamics, carbon negativity through operational changes alone appears difficult to achieve. This has direct implications for certification schemes such as Sustainable Wines of Great Britain: without explicit accounting for prior land use and SOC stock changes, audit frameworks risk misclassifying operationally efficient but SOC-depleting vineyards as low-carbon, while failing to credit operationally intensive but SOC-accruing sites.

5.4 The average GWP100 of English grapes falls at the lower end of the global viticultural carbon footprints, in part due to sequestration

The mean GWP100 of $+0.255 \text{ kg CO}_2\text{-eq kg}^{-1}$ falls in the lower end of the global viticulture LCA range (approximately 0.09 to $0.85 \text{ kg CO}_2\text{-eq kg}^{-1}$) (Silva & Silva, 2022; Ferrara & De Feo, 2018; Litskas et al., 2020; Litskas et al., 2017; Poore & Nemecek, 2018; Steenwerth et al., 2015). This value likely reflects two factors: the lower agrochemical and fuel intensity of English viticulture relative to irrigated Mediterranean systems, and the net-negative SOC contribution from cropland-converted sites drawing the sector mean downwards. Direct numerical comparison with existing studies is limited by methodological inconsistency in the treatment of LUC and carbon stocks (see Section 1.1).

5.5 East Anglia exhibits carbon negativity, consistent with its predominantly arable land use

The descriptive regional GWP100 means were lowest in eastern England (Norfolk, Essex, Suffolk) and highest in southern and south-western regions. The pattern mirrors the regional distribution of arable land - cereal landscapes predominate in the east (DEFRA, 2025), while permanent pasture dominates the South Downs and South West. This is consistent with prior land use as the dominant driver of GWP100. Small within-region sample sizes ($n = 3\text{--}8$) preclude formal analysis here. Targeted sampling, stratified by prior land-use type within each county, would permit formal testing.

Although IPCC Tier 1 prescribes the cropland-as-sink / pasture-as-source relationship, the model did not determine which vineyards I sampled, nor does it set vineyard operational emission profiles. Conventional arable conversions could in principle have demanded high N inputs that overwhelmed SOC gains - they did not (as discussed in section 5.3). Conditional on Tier 1's accuracy, the regional pattern therefore reflects a genuine empirical regularity in establishment behaviour: vineyards in arable-dominated regions have tended to convert former cropland, while those in pasture-dominated regions have tended to convert pasture. Establishment decisions in this sample appear constrained by local landscape composition, so spatial policy levers, targeting new plantings to conventional cropland-rich regions, would deliver carbon-negative expansion without requiring per-site land-use criteria.

5.6 Policy on new plantings could lead to significant carbon mitigations

Scaled to 1000 ha of new planting, land-use choice determines whether expansion delivers a net annual carbon sink of $-683 \text{ t CO}_2\text{-eq yr}^{-1}$ (cropland conversion; 95% bootstrap CI: -1123 to -241) or a net source of $+3163 \text{ t CO}_2\text{-eq yr}^{-1}$ (pasture conversion; CI: $+2163$ to $+4002$), a difference of $\sim 3846 \text{ t CO}_2\text{-eq yr}^{-1}$, equivalent to the annual tailpipe emissions of ~ 2600 UK passenger cars (DfT, 2024: $1.5 \text{ t CO}_2\text{-eq yr}^{-1}$ per UK passenger car). At the sector's current growth rate of $\sim 630 \text{ ha yr}^{-1}$ (WineGB, 2025), each annual cohort of new planting carries a climate stake of approximately $2,400 \text{ t CO}_2\text{-eq yr}^{-1}$, equivalent to $\sim 1,600$ cars.

At European-comparable scale, the implications are larger. If English viticulture were to reach 3% of national UAA ($\sim 267,000 \text{ ha}$, Section 1.1), the difference between an all-cropland and an all-pasture conversion trajectory would reach approximately $1.0 \text{ Mt CO}_2\text{-eq yr}^{-1}$, equivalent to the annual emissions of $\sim 694,000$ UK cars. At the 38% cropland conversion rate observed in this sample, the sector's net balance at that scale would remain positive ($+454,000 \text{ t CO}_2\text{-eq yr}^{-1}$). Only deliberate targeting of cropland conversion, shifting the observed 38% cropland rate substantially upward, would generate net negativity at scale.

Targeting conventional arable land to establish vineyards on, via planning guidance, Sustainable Wines of GB criteria, or carbon payments, is a cost-effective route to a net-negative sector. No operational change can substitute for the potential of this upstream decision.

5.7 Limitations and future directions

The IPCC (2019) Tier 1 SOC model applies global stock change factors disaggregated only by climate zone and soil type, with no vineyard-specific land-use category. Vineyards fall under a broad "permanent cropland" class shared with coffee plantations and orchards, and no provision for management effects (tillage, cover crops, carbon inputs) on permanent crops. The cases of cropland sites with variable land use histories in section 4.3.1 illustrate the limits of IPCC Tier 1 SOC modelling at fine management resolution: the model captures broad trajectories from prior land-use category but struggles to represent site-specific rotation or fallow histories that shift the effective baseline. English vineyard soils, spanning chalk, greensand and clay substrates, likely exhibit SOC responses well beyond what a single climate-zone factor can resolve, and the data here indicate substantial management variation that the model holds constant. Cover cropping and

reduced tillage are known to increase vineyard SOC relative to conventional management (Payen et al., 2021). Multi-year direct SOC sampling across the three groups would test Tier 1's directional predictions and incorporate management effects. Strengthening this data would allow this study to emphasise the effects of land-use change on biological carbon stocks and perhaps offer insights for other regions where viticulture is expanding.

The cradle-to-farmgate boundary excludes winery, bottling, packaging, and distribution emissions, which typically dominate full cradle-to-consumer wine footprints (Ferrara and De Feo, 2018). The winery section of this project's questionnaire was completed by 13 sites and represents an unanalysed dataset. Combining these data with secondary packaging and distribution emission factors would extend the boundary to a full cradle-to-bottle LCA, yielding the first national carbon footprint estimate for English wine itself.

Only GWP100 is reported here, but the HESTIA inventory generates secondary indicators, water use, eutrophication, terrestrial acidification, biodiversity loss, not analysed here. Reporting these alongside GWP100 would test whether the land-use selection logic identified for carbon also holds for other impact categories, or whether trade-offs exist. HESTIA's other indicators would likely penalise agrochemical-intensive established vineyards and habitat-converting pasture sites further, likely reinforcing rather than offsetting the cropland recommendation, though this remains untested here.

Subgroup sizes of 12–15 mean bootstrap CIs quantify within-sample uncertainty but cannot guarantee national representativeness within each land-use category, and the study held management variables broadly constant to isolate the land-use effect. Scaling sampling within each category and isolating specific management interventions, (e.g., cover cropping, reduced tillage, biochar, electrified machinery) would identify which operational levers can shift the carbon balance once SOC equilibria are reached. This study's framework transfers directly to other perennial sectors (orchard fruit, soft fruit, hops) that are expanding over agricultural land. Comparative LCA across these sectors would clarify perennial expansion's contribution to England's agricultural carbon targets.

5.8 Conclusions

English viticulture is not, on average, carbon-negative, but one third of vineyards, at least in my sample, already are, and the capacity for future English vineyards to be carbon-negative is real and within reach. That capacity is determined almost entirely by a single upstream decision: the choice of site based on prior land use. Conversion from conventional arable cropland drives net soil and biomass carbon sequestration that can offset all operational emissions during the establishment phase. Conversion from permanent pasture generates an SOC source that no operational efficiency can overcome. Among operational sources, agrochemicals and fossil fuel combustion are the largest and most tractable targets. Steel infrastructure is a non-trivial and previously overlooked contributor. With vineyard area expanding faster than in traditional wine countries, site-selection decisions made now will determine whether English viticulture contributes to or subtracts from England's agricultural carbon balance. This dataset makes the prescription clear: prioritise planting vineyards on conventional, carbon-depleted cropland.

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Finally, I want to thank my family and friends, who have patiently endured a year of relentless discussion about vineyards, carbon accounting, and English wine. Their support mattered more than they know.

Life is too short to drink bad wine; that is for us and for the planet.

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Appendices

Supplementary Tables and Figures

Table S1: Emissions included and modelling approach on HESTIA. If both a Tier 2 and Tier 1 model are available, the Tier 2 model will be used if there is sufficient activity data. Full documentation of HESTIA is available in Poore *et al* (2021)¹.

Emission / Resource Use	Process	Database / Model
All emissions and resource uses	Input production (e.g., fertilisers, soil amendments, electricity, fuel)	HESTIA, BAFU, World Steel, and Plastics Europe
CO₂, N₂O (direct and indirect), NH₃, NO_x, SO₂, PM10, PM2.5 to air	Fuel combustion	EMEP-EEA (2019); IPCC (2019) Tier 1
N₂O, NO_x to air	Organic and inorganic fertiliser application	Stehfest and Bouwman (2006) Tier 2; IPCC (2019) Tier 1
NH₃ to air	Organic fertiliser application	Webb <i>et al</i> (2012); Sintermann <i>et al</i> (2012)
NH₃ to air	Inorganic fertiliser application	EMEP-EEA (2019) Tier 2; IPCC (2019) Tier 1
NO₃⁻ to groundwater	Organic and inorganic fertiliser application	Poore & Nemecek (2018)
N₂O, NO_x to air	Crop residues left on field	Stehfest and Bouwman (2006) Tier 2; IPCC (2019) Tier 1
NH₃ to air	Crop residues left on field	de Ruijter <i>et al</i> (2010)
N₂O to air (indirect)	Organic and inorganic fertiliser	IPCC (2019) Tier 1
CO₂ to air	Urea application	IPCC (2019) Tier 1
CO₂ to air	Lime and dolomite application	IPCC (2019) Tier 1
CH₄, N₂O (direct and indirect), NH₃, NO_x, SO₂, PM10, PM2.5 to air	Crop residue burning	Akagi <i>et al</i> (2011); IPCC (2019) Tier 1
CH₄ to air	Flooded rice cultivation	IPCC (2019) Tier 2

CO₂ to air	Management change: soil carbon stock change	IPCC (2019) Tier 2; Tier 1
CO₂ to air	Land use change: above ground biomass, below ground biomass, soil carbon stock change	IPCC (2019) Tier 1
CH₄, N₂O (direct and indirect), NH₃, NO_x, to air	Land use change: natural vegetation burning	IPCC (2019) Tier 2; Tier 1
CH₄, N₂O to air	Drained peat soils	IPCC (2019) Tier 1

Table S2: The primary indicator of this study.

Indicator	Characterisation Model	Emissions / Resource Uses / Midpoints Characterised
<u>Primary Indicator</u>		
Greenhouse Gas Emissions	IPCC AR6 100-year factors	CO ₂ , CH ₄ , N ₂ O, HFC's, PFC's, SF ₆ , NF ₃ to air

Table S3. Mean GHG emission source contributions by prior land-use category (kg CO₂-eq kg⁻¹ grape, IPCC GWP100). Positive values = net GHG source; negative values = net carbon removal. LUC = land-use change. SOC = soil organic carbon. Category means are independently averaged; sum may differ slightly from net GWP100. n = 15 Cropland, 12 Pasture, 13 Vineyard. Operational total = sum of all rows above SOC and biomass terms. For the established vineyard group, SOC and Biomass are zero by construction (20-year IPCC Tier 1 equilibrium), so the operational total equals Net GWP100.

Emission source	Cropland	Pasture	Vineyard	Overall
SOC Stock Change	-0.137	+0.715	0.000	+0.163
Below-Ground Biomass (LUC)	-0.218	-0.218	0.000	-0.147
Above-Ground Biomass (LUC)	-0.212	-0.213	0.000	-0.143
Fossil Fuel Combustion	+0.117	+0.067	+0.129	+0.106
Agrochemicals	+0.088	+0.089	+0.109	+0.095
Steel (Infrastructure)	+0.079	+0.061	+0.041	+0.061
N ₂ O Fertiliser (Nitrif./Denitrif.)	+0.053	+0.031	+0.077	+0.055
Crop Residue Addition	+0.037	+0.022	+0.060	+0.040
Urea & Lime	+0.000	+0.009	+0.044	+0.017
Wood (Infrastructure)	+0.001	+0.008	+0.018	+0.009
Net GWP100	-0.192	+0.572	+0.478	+0.255
'Operational Emissions' (Everything but SOC and Biomass)	+0.375	+0.287	+0.478	+0.383

Table S4. Mean GHG emission source contributions by prior land-use category ($\text{kg CO}_2\text{-eq ha}^{-1}\text{ yr}^{-1}$). Per-ha values = per-kg value $\times$ site yield ($\text{kg ha}^{-1}\text{ yr}^{-1}$). Validated against HESTIA Cycle export (functional unit = 1 ha): mean absolute difference < 0.2% per site.

Operational total = sum of all rows above SOC and biomass terms. For the established vineyard group, SOC and Biomass are zero by construction (20-year IPCC Tier 1 equilibrium), so the operational total equals Net GWP100.

Emission source	Cropland	Pasture	Vineyard	
SOC Stock Change	−552	+3,735	0	
Below-Ground Biomass (LUC)	−1,030	−1,018	0	
Above-Ground Biomass (LUC)	−1,004	−993	0	
Fossil Fuel Combustion	+594	+391	+621	
Agrochemicals	+389	+450	+446	
Steel (Infrastructure)	+378	+321	+142	
N₂O Fertiliser (Nitrif./Denitrif.)	+365	+93	+188	
Crop Residue Addition	+172	+115	+204	
Urea & Lime	+1	+41	+97	
Wood (Infrastructure)	+6	+28	+61	
Net GWP100	−683	+3,163	+1,569	
‘Operational Emissions’ (Everything but SOC and Biomass)	+1,905	+1,439	+1,569	+1,656

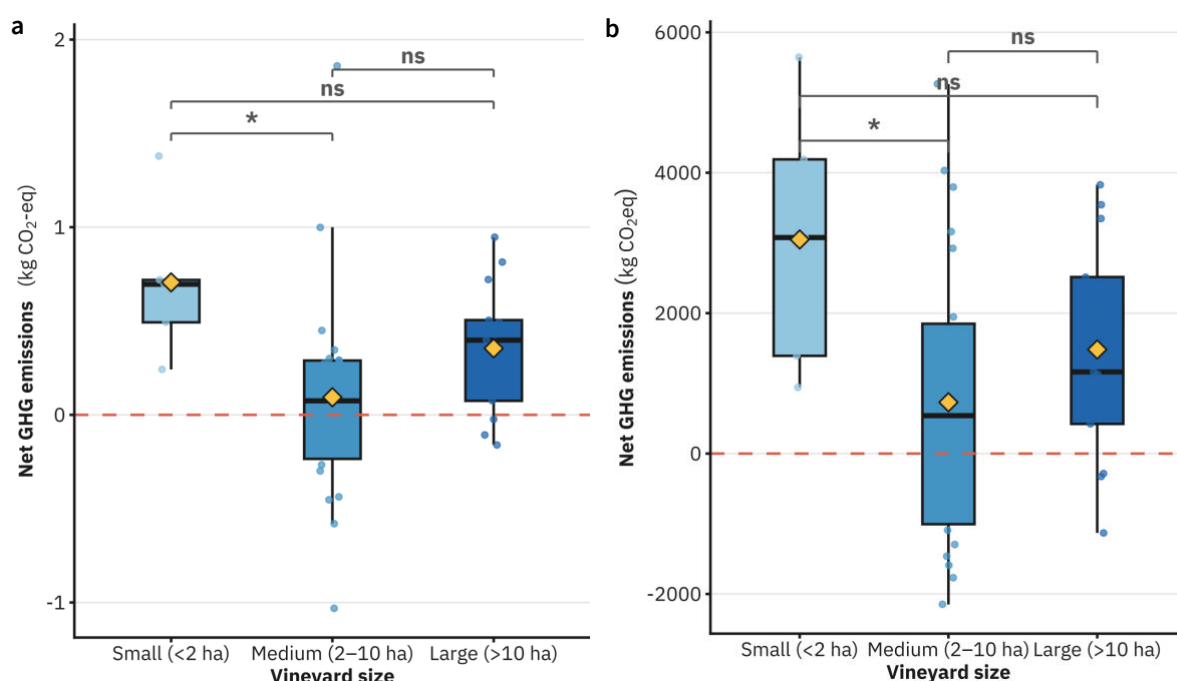


Figure S1. GWP100 distribution of English vineyard grape by vineyard size . (a) GWP100 kg^{-1} grape by vineyard size. (b) GWP100 $\text{ha}^{-1}\text{ yr}^{-1}$ of vineyard by vineyard size. Amber diamonds (◆) represent group mean. Red dashed line (---) represents carbon neutrality. Boxplots display median $\pm$ IQR and whiskers are $1.5 \times$ IQR. Significance brackets are Tukey adjusted HSD (* $p < 0.05$; ns $p \geq 0.05$).

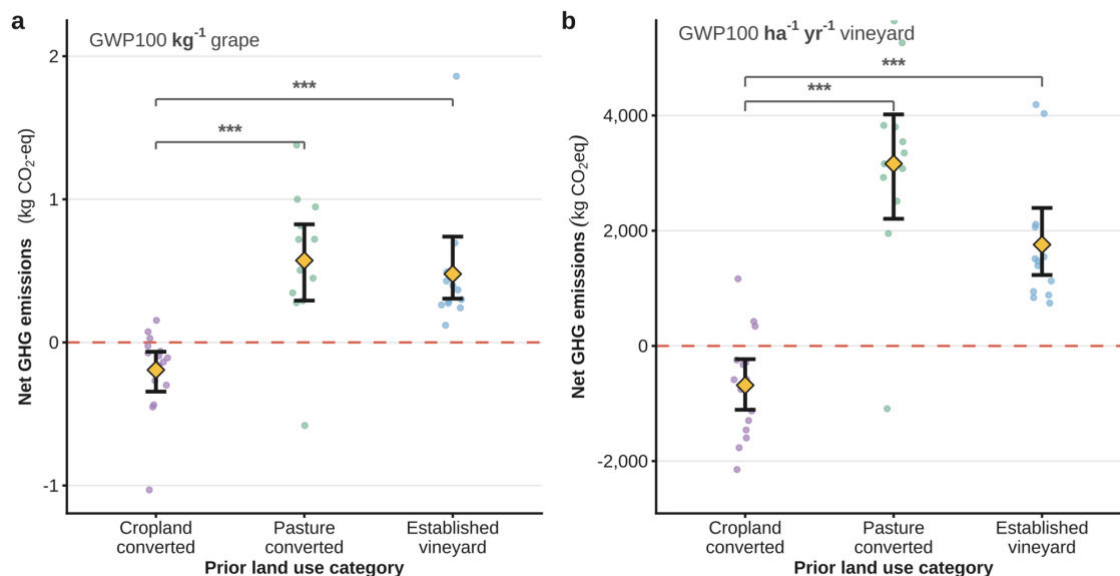


Figure S2. GWP100 by prior land use category with bootstrap 95% confidence intervals on the group mean (10,000 resamples). (a) GWP100 kg⁻¹ grape produced. (b) GWP100 ha⁻¹yr⁻¹ of vineyards by prior land-use category. Amber diamonds (◆) represent group mean. Red dashed line (---) represents carbon neutrality. Black Bars represent 95% confidence interval of the mean. Significance brackets are Tukey adjusted HSD (***) $p < 0.001$; ns $p \geq 0.05$.

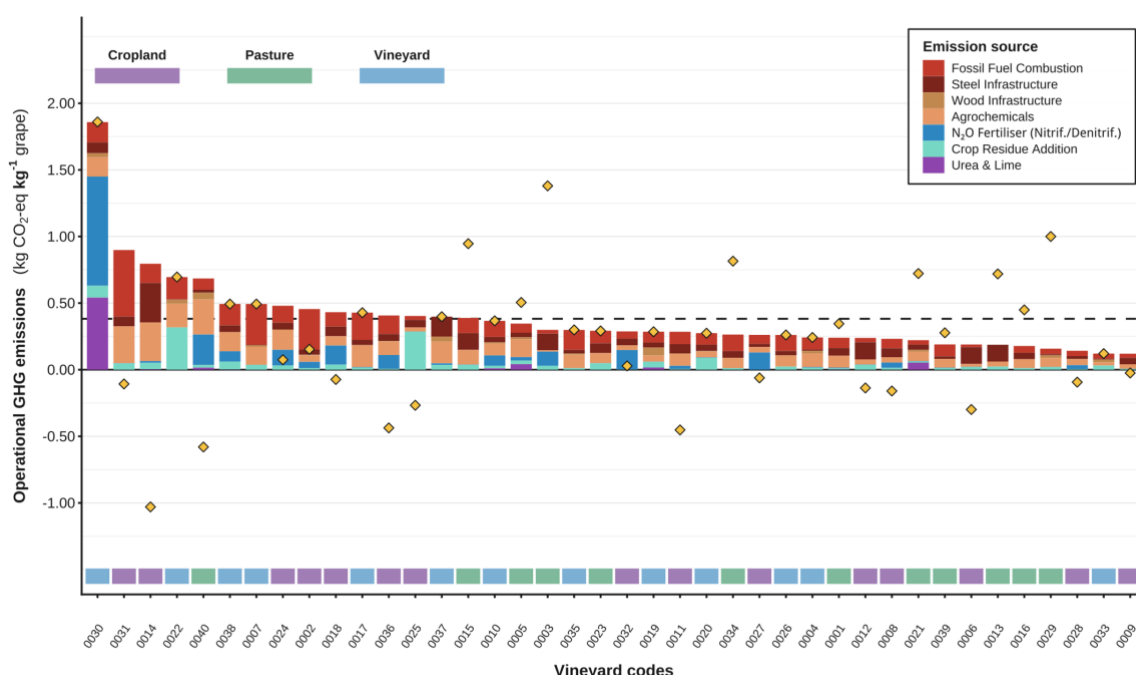


Figure S3. Per-vineyard operational GHG emissions. Stacked bars show the contribution of seven operational source categories (fossil fuel combustion, steel and wood infrastructure, agrochemicals, N₂O fertiliser, crop residue addition, urea and lime) to each vineyard's operational footprint, in kg CO₂-eq kg⁻¹ grape (GWP100, IPCC AR6). Vineyards (n = 40) are ordered left to right by descending operational total. Amber diamonds (◆) show each site's net GWP100, including biomass and soil-carbon stock changes from land-use change; the offset between diamond and bar therefore reflects the magnitude of LUC sequestration or emission at each site. The black dashed line (---) marks the full 40 sample mean operational emissions. The coloured strip by the x-axis shows each vineyard's prior land-use category.

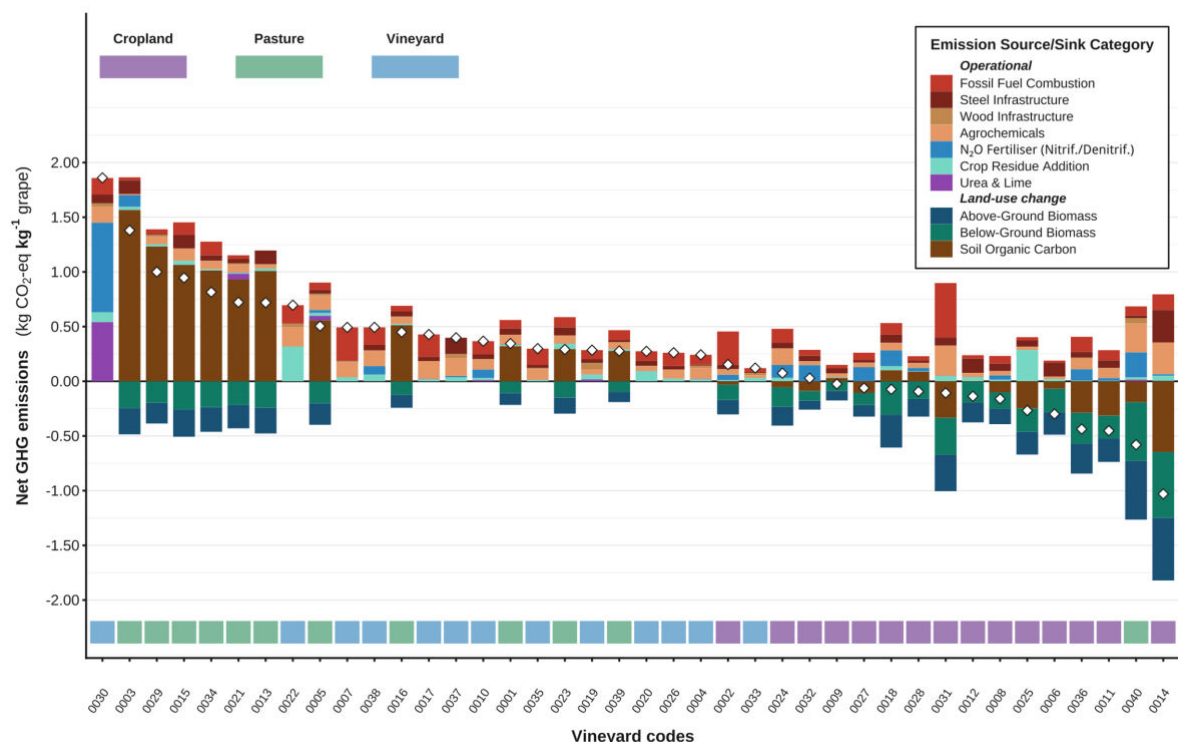


Figure S4. Per-vineyard net GHG emissions by source. Stacked bars show the contribution of ten emission and sequestration categories - seven operational (fossil fuel combustion, steel and wood infrastructure, agrochemicals, N₂O fertiliser, crop residue addition, urea and lime) and three land-use change (above-ground biomass, below-ground biomass, soil organic carbon) - to each vineyard's net carbon footprint, in kg CO₂-eq kg⁻¹ grape (GWP100, IPCC AR6). Vineyards (n = 40) are ordered left to right by descending net GWP100. Positive bars indicate emissions; negative bars indicate carbon sequestration through biomass accumulation and soil carbon stock change. White diamonds (◇) show each site's net GWP100 summing all positive and negative contributions. The coloured strip below the x-axis indicates each vineyard's prior land-use category (cropland, pasture, or established vineyard).

Management report

This project was ambitious for an MBIol thesis from the outset and, naturally, encountered several bumps along the way. Recruiting 40 vineyard participants required multiple rounds of outreach, including public engagement at vineyard festivals and SID events. Data collection was originally intended to run from early October to mid-February; in reality, my first vineyard was sampled on 30 October and the final one on 28 February, cutting the timeline for data upload finer than I would have liked.

Visiting many vineyards in person was a deliberate choice to improve participant engagement and data quality, which meant finding a way to keep a car in Oxford during the early months of 2026. This was made possible through the kindness of Alena Goebel from the HESTIA team, who generously allowed me to use her driveway while she lived in Oxford. Without this support, I genuinely do not know how the fieldwork could have been completed to the standard achieved here.

Participant rejection rates were also higher than expected, and towards the end of data collection I was fortunate to receive help from another fantastic member of the HESTIA team, Fleur Delany, who assisted in sampling the additional 5 vineyards needed to complete the dataset. The eventual adoption of IPCC Tier 1 modelling was largely determined by the type and consistency of soil data obtained through vineyard interviews, which may limit some of the conclusions drawn in this thesis.

Transferring all 40 questionnaires from paper sheets into a structured digital dataset was both time-consuming and mentally demanding, but I am glad I persisted with it. Adapting HESTIA to the specific needs of this project through glossary updates and model checks was also a steep learning curve, requiring a level of self-management and technical discipline far beyond anything I had previously experienced. Throughout this project, I was tasked to purchase some wine for a wine tasting I co-hosted with Dr Andy Wood in Oxford. This was a real pleasure but a significant use of time in which I had to prepare materials for an evening discussing English wine and my research.

Lastly, I would like to formally register a complaint against the county of Devon for the severe flooding it offered me while travelling to vineyards there.