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ORIGINAL RESEARCH ARTICLE

Soil types as extrinsic cues differentially shape sensory perception of German Riesling wine

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ABSTRACT

Despite the lack of consensus regarding the effects of different soils on wine flavour, the simplification of terroir to soil type has become increasingly common in wine marketing, particularly for German Riesling. To examine the effects of this strategy on sensory perception, twenty German Rieslings from four commonly marketed soil types (*Buntsandstein*, *Löß*, *Muschelkalk*, and *Schiefer*) were evaluated for aroma, taste, and mouthfeel attributes (rate-all-that-apply) by a panel of twenty wine experts, first without and then with each wine's soil type given as an extrinsic informational cue. While ratings from the uninformed tastings suggest baseline differences among Rieslings from the various soils, the provision of soil type cues resulted in more extensive discrimination, particularly in terms of attributes related to minerality (*earthy*, *chalky*, *marine*, *flinty*, and *salty*). Soil type-dependent changes in ratings suggest distinct *a priori* conceptions for each soil shaped the panel's expectations and differentially altered their perception, though further work is needed to determine whether nonexpert consumers would be similarly biased by these cues. For wine soil typing to be a viable marketing strategy, a well-defined "image" of each soil would need to be communicated to consumers, to ensure their expectations are set to trigger perception of the desired sensory properties.

KEYWORDS: Expectation, minerality, Riesling, sensory perception, terroir, wine

INTRODUCTION

Widely regarded as a fundamental antecedent to wine quality, terroir (from the French *terre*, meaning "land"), may be conceptualised as the collection of interactions between the grapevine and its physical environment (van Leeuwen, 2022). Vine development, grape ripening, and consequently the sensory properties of wine produced are influenced by many external factors including weather and climate, human intervention, and the prevailing microbiome (Seguin, 1986; van Leeuwen and Seguin, 2006; Bokulich *et al.*, 2016), which altogether give wine a "sense of place."

Regarding the geological aspects of terroir, the notion that minerals derived from various soil substrates can be taken up by the grapevine and confer distinct sensory properties to wine has largely been disproven (Maltman, 2013; Parr *et al.*, 2018). The influence of soil is more likely indirect, controlling such parameters as root penetration depth, nutrient availability, and water-holding capacity (Huggett, 2006; Willwerth and Reynolds, 2020). However, there is no clear consensus regarding the differential effects of specific soil types: while some studies have found significant differences in the flavour profiles of wines originating from different soils (de Andres-de Prado *et al.*, 2007; Löhnertz *et al.*, 2008; Bauer *et al.*, 2011), others have demonstrated that such effects, if any, are negligible in comparison to those from other aspects of terroir, particularly local winemaking practices and climatic conditions (Rankine *et al.*, 1971; Noble, 1979; Wahl, 1988; Bader and Wahl, 1996; Fischer *et al.*, 1999).

Nonetheless, it has become increasingly common in wine marketing to reduce terroir down to soil type. Information regarding the geological substrate found at vineyard sites, such as slate or limestone, is often provided to consumers, in some cases even replacing geographical indications on bottle labels, price lists, etc. (Bauer *et al.*, 2011). This appears especially true for Riesling in Germany since techniques such as barrel ageing and malolactic fermentation are not widely used; by minimising the impact of winemaking, it is believed more genuine expression of the environment can be achieved (Robinson, 2015; Bauer *et al.*, 2011). Naming specific soil types when marketing wine presumably affects how it is perceived, though any precise outcomes from this strategy have yet to be determined.

Extrinsic informational cues can give rise to expectations that a product will exhibit certain characteristics, consequently modifying perception during consumption (Deliza and MacFie, 1996; Brochet and Morrot, 1999). Consumers will perceive added value, particularly from information that solidifies the link between a product and its origin, such as explicit mentions of production size or sustainable practices (Lenglet, 2014; Capitello *et al.*, 2021). However, for such cues to effectively trigger consumer associations and shape their expectations, there must exist a consistent *a priori* "image" of the place of origin (van Ittersum *et al.*, 2003). That is to say, with regard to the soil typing of wine, terms such as "slate" or "limestone" must carry meaning, but given the lack of consensus regarding the effects of different soils on wine flavour, it is uncertain whether this assumption is valid.

We propose tasters' preconceptions of soil types can be determined by controlling the information they receive during sensory evaluation, as has been done in previous studies to reveal biases and expectations (Siegrist and Cousin, 2009; Peterson, 2014; Boncinelli *et al.*, 2016). For the study presented here, our sensory panel evaluated German Rieslings first without and then with cues informing them of the soil type each wine came from. Between the uninformed and informed tastings, sensory perception was expected to shift differentially according to any panel preconceptions, which would confirm each soil type has a distinct "image" and thus justify how these wines are being marketed.

MATERIALS AND METHODS

1. Wines

Twenty German Riesling wines from the 2020 and 2021 vintages were evaluated in this study. Wines were chosen from vineyards cultivated on one of four commonly marketed soil types: *Buntsandstein* (coloured sandstone), *Löß* (loess), *Muschelkalk* (shell-bearing limestone), and *Schiefer* (slate), as stated by each producer. To ensure variance, each soil type was represented by five wines from different producers throughout winegrowing regions where Riesling is the predominant white variety (Supplementary Table 1), though the influence of producer, region, and physicochemical composition was not the focus of our study. All wines were donated by or purchased directly from each producer.

Additionally, to evaluate the effects of each soil type cue under limited influence from other variables, a composite control wine was prepared by blending all twenty wines in equal proportions one day prior to the study. Bottles were filled under nitrogen, sealed with screwcap closures, and stored in the same conditions as the other wines until sensory evaluation.

2. Participants

Twenty participants (4 female, 16 male) with a mean age of 47 (range 25–67) comprised the panel of judges for this study, all considered wine experts according to the criteria proposed by Parr *et al.* (2002). Email invitations were sent to Weincampus alumni and other wine industry affiliates in Germany. The study was presented as a unique opportunity to taste vineyard-designated Riesling from throughout the country, as well as network with fellow industry members. Those who responded with interest were sent additional information regarding the study's agenda and format before formally consenting to participate, in keeping with the ethical requirements of the Weincampus Neustadt, Dienstleistungszentrum Ländlicher Raum (DLR) Rheinpfalz. The study was conducted in accordance with the Declaration of Helsinki for studies involving human subjects.

TABLE 1. Aroma attributes and the ingredients used for each standard. A 2021 Riesling from Henkell Sektkellerei (Wiesbaden, Germany) was used as the base wine. All chemicals were from Merck (Darmstadt, Germany). With the exception of *chalky*, ingredients were added to 100 mL base wine, and any insoluble solids were extracted for approximately one hour before removal by filtration or decanting. Standards (30 mL) were presented in 10960 Sensus wineglasses (Zwiesel Kristallglas, Zwiesel, Germany), labelled and covered with plastic lids.

Aroma attribute	Standard ingredients
apple/pear	20 mL apple juice (Rewe, Cologne, North Rhine-Westphalia), 20 mL pear juice (Lösch's, Ramstein-Miesenbach, Rhineland-Palatinate)
citrus	25 mL freshly squeezed lemon juice, 20 mL freshly squeezed grapefruit juice
peach/apricot	40 mL peach/apricot juice blend (Eos, Weinstadt, Baden-Württemberg)
tropical	40 mL mango-passionfruit juice blend (Rewe)
sweet/sugary	15 g honey (Bienenwirtschaft Meißen, Meißen, Saxony), 10 g fig marmelade (Bonne Maman, Breuberg, Hessen)
floral	10 mL elderflower syrup (Rewe), 20 uL linalool (2 µg/µL in ethanol)
fresh/grassy	50 g diced cucumber, 2 g fresh grass
vegetal	10 g canned green beans (Bonduelle, Villeneuve d'Ascq, Hauts-de-France), 15 g diced bell pepper
herbal	0.5 g green tea (Costco Kirkland Signature, Issaquah, Washington), 0.5 g *herbes de Provence* (Ostmann, Dissen am Teutoburger Wald, Lower Saxony)
spicy	0.2 g ground cinnamon, 0.2 g ground nutmeg, 0.1 g ground white pepper (Ostmann)
yeasty/lactic	1 g yeast (Uniferm, Werne, North Rhine-Westphalia), 1 g butter (Rewe), 1 g yoghurt (Weihenstephan, Freising, Bavaria)
reduced	20 uL sodium sulfide (0.5 µg/µL in water)
nutty/oxidised	1 g roasted almond butter (Rewe), 5 mL Pedro Ximénez sherry (Lustau, Jerez de la Frontera, Andalusia)
TDN	10 uL 1,1,6-trimethyl-1,2-dihydronaphthalene (0.1 µg/µL in ethanol)
chalky	1 g powdered chalk, 5 uL geosmin (0.05 ng/µL in ethanol), in 100 mL of 25 % (v/v) base wine/water solution
earthy	2 g chopped portabello mushrooms, 10 µL geosmin (0.05 ng/µL in ethanol)
flinty	10 uL benzylmercaptan (1 ng/µL in ethanol)
marine	1 g roasted seaweed (Kreyenhop & Kluge Miyako, Oyten, Lower Saxony), 10 mL dimethyl sulfide (0.25 µg/µL in ethanol)
metallic	10 uL 1-octen-3-one (0.1 µg/µL in ethanol)

3. Sensory evaluation

The study took place in the sensory laboratory at Weincampus Neustadt. Upon their arrival, the participants were asked to smell aroma standards to familiarise themselves with the attributes to be evaluated (Table 1). Taste and mouthfeel attributes were also evaluated (*sweet*, *sour*, *salty*, *bitter*, *alcohol*, *body*, and *length*), though no standards for these were provided. Attributes were selected by sensory science staff members at the Weincampus with prior research experience with Riesling. The list of attributes was compiled from those used in several previous studies on Riesling (Fischer *et al.*, 1999; Bauer *et al.*, 2011; Douglas *et al.*, 2001; Schüttler *et al.*, 2015), and additionally included terms often used to describe minerality (Ballester *et al.*, 2013; Maltman 2013, Heymann *et al.*, 2014; Rodrigues *et al.*, 2015). It should be noted this study took place in German, and the attributes here have been translated as closely as possible into English.

Judges were seated at individual booths with computers where FIZZ Software v2.5 (Biosystèmes, Couternon, France) was used for sensory evaluation. The study consisted of two 90-minute sessions, separated by a onehour break. Opening and pouring (30 mL) of the wines began in a separate room approximately one hour before the start of each session. Wines were served at ambient temperature (20 ºC) in clear DIN 10960 Sensus wineglasses (Zwiesel Kristallglas, Zwiesel, Germany), each labelled with a random three-digit code and covered with a plastic lid. The wines were served in a balanced random order for each judge according to a Williams Latin square design to control for presentation order and carryover effects.

During session 1, the judges knew only that the wines were German Rieslings from 2020 or 2021. The control wine was presented to each judge in quadruplicate (n = 4), while the 20 original wines were each presented once. For session 2, the judges were made aware of the soil type from which these wines originated, with each wine's soil

type appearing on FIZZ alongside its three-digit code. The 20 original wines were again each presented once, while the control was presented a total of 8 times: each of the 4 soil types (*Buntsandstein*, *Löß*, *Muschelkalk*, and *Schiefer*) was shown twice for the control, such that the effect of each cue on the perception of the control was evaluated in duplicate (n = 2 for each soil type). Accounting for replication, each judge conducted in total 24 evaluations during session 1, and 28 evaluations during session 2.

Rate-all-that-apply (RATA) was used for sensory evaluation (Ares *et al.*, 2014). Aroma attributes were presented on a single page on FIZZ in a random order for each judge, followed by a second page with randomised taste and mouthfeel attributes. Judges rated the intensity of attributes they deemed perceptible by clicking on an unstructured line scale anchored by "not present" and "very intense" (valued from 0 to 100); unrated attributes were assumed an intensity of 0. Judges were instructed to pause in between wines as needed to avoid fatigue; water and flatbread were available for the judges throughout the study. They proceeded at their own pace, without consulting those around them, and the majority completed each session in less than 90 min.

4. Data analysis

All data was analysed in RStudio v2023.03.0+386 (Boston, Massachusetts, USA) running R v4.2.1, with the additional packages *reshape2*, *lmerTest*, *FactoMineR*, *emmeans, multcomp*, and *factoextra*. A confidence level of 95 % was used for all significance testing ($\alpha = 0.05$).

To compare the wines and soil types from session 1, a two-way multivariate analysis of variance (MANOVA) using Wilk's lambda was first conducted using *replicate*, *wine*, and *soil* as the fixed effects with the *wine* effect nested within *soil*. Given the control was evaluated in quadruplicate (n = 4) by each judge, the *replicate* effect was included in the MANOVA model to assess panel repeatability. The control was included as its own category, alongside *Buntsandstein*, *Löß*, *Muschelkalk*, and *Schiefer*, under the *soil* effect. To determine which attributes characterised each soil type, univariate analysis of variance (ANOVA) was conducted for each attribute using a two-way mixed model with *soil* and *judge* as fixed and random effects, respectively. Attributes for which *soil* was a significant source of variance were used for principal component analysis (PCA). The correlation matrix of mean ratings for these attributes, calculated across judges for each wine, was used to construct the wine product space. Marginal means for each attribute were calculated for each soil type, after which they were compared *post hoc* using Tukey's honestly significant difference (HSD) test.

Data from session 2 was analysed in a similar manner as the data from session 1, though the controls were categorised according to the soil type with which they were labelled. Additionally, the *soil*replicate* interaction term was included in the MANOVA model, to check judge repeatability when evaluating each of the differently labelled controls (n = 2 for each soil type). ANOVA and PCA were conducted as described above, after which marginal means were also calculated and compared via Tukey's HSD.

To examine more closely the effects of each soil type cue, the difference in ratings between session 2 and session 1 (Δ, "delta") was calculated for each judge, attribute, and wine. A positive Δ would indicate a judge perceived an attribute more intensely upon knowing a wine's soil type, whereas a negative Δ would indicate a decrease in perceived intensity. For the labelled controls in session 2, Δ values were calculated by subtracting the mean for the unlabelled control from session 1 (n = 4 for each judge). MANOVA and ANOVA were conducted as described above for session 2, but using Δ values rather than intensity ratings. PCA was done using mean Δ values for each soil type.

RESULTS

1. Session 1: Uninformed tastings

The effects of *soil* and *wine* (nested within *soil*) were significant according to MANOVA, indicating significant differences among soil types and among wines within each soil type. The *replicate* effect was not significant, suggesting judges performed repeatably in their evaluations of the composite control wine (n = 4). According to ANOVA, *soil* was a significant source of variance for eight aroma attributes as well as four taste and mouthfeel attributes (Table 2); the remaining attributes were excluded from subsequent analysis of the data from session 1.

The plots generated from PCA illustrate the perceived differences and similarities among wines (Figure 1a) based on these significant sensory properties (Figure 1b). Explaining 43.9 % of the variance, PC1 appears to be driven mainly by differences between wines from *Muschelkalk* and *Schiefer*. All *Muschelkalk* wines (M1, M2, M3, M4, and M5) are found in the positive direction of PC1, correlated primarily with *TDN*, *bitter*, and *sour*, and to a lesser extent also *nutty/oxidised*, *spicy*, and *herbal*. With the exception of wine S4, the *Schiefer* wines (S1, S2, S3, and S5) tend toward the negative direction of PC1, correlated with *tropical*, *floral*, *sweet/sugary* (aroma), and *sweet* (taste). Wines M4 and S5 were rated highly in *yeasty/lactic*, *nutty/oxidised*, and *body*, and lie separate from the other wines along PC2. Wines from *Buntsandstein* (B1, B2, B3, B4, and B5) and *Löß* (L1, L2, L3, L4, and L5) are generally closer to the centre of the score plot, along with the control (Ctrl). Despite the likelihood of chemical and sensory interactions upon blending twenty wines (e.g. enhancing or masking effects), the control is located just below the centre of the score plot along PC2, which explains only 20.5 % of the overall variance. The situation of the control in this region of the plot, where attribute loadings are generally absent, suggests it is a proper "average" uncharacterised by any particular attributes.

A comparison of the marginal means for each soil type suggests *Schiefer* and *Muschelkalk* yield the most distinct wines (Table 2). *Muschelkalk* wines were rated exceptionally high for *TDN* and *sour*. They were also the most *nutty/*

TABLE 2. Marginal means for attributes that differed significantly among soil types in session 1 (uninformed tastings), indicated by different lowercase letters across rows (a = 0.05).

	Buntsandstein	Löß	Muschelkalk	Schiefer	Control
tropical.A	17.1 abc	18.8 bc	10.6 a	23.2 c	14.5 ab
sweet/sugary.A	12.9 a	16.7 ab	10.6 a	23.5 b	9.3 a
floral.A	22.4 ab	22.8 ab	18.4 a	30.6 b	15.1 a
herbal.A	20.9 ab	17.2 ab	23.1 b	17.0 ab	14.0 a
spicy.A	18.8 ab	16.2 a	26.6 b	20.6 ab	15.8 a
yeasty/lactic.A	6.6 ab	7.9 ab	9.4 ab	12.3 b	5.4 a
nutty/oxidised.A	9.7 a	11.5 ab	18.8 b	10.1 a	5.3 a
TDN.A	13.6 a	10.3 a	26.8 b	10.1 a	7.4 a
sweet.T	36.2 b	40.5 bc	25.5 a	47.1 c	33.2 ab
sour.T	45.0 b	43.3 b	53.0 c	36.3 a	44.8 b
bitter.T	24.5 ab	23.0 a	31.2 b	21.8 a	20.6 a
body.M	46.9 a	53.1 b	46.7 a	53.0 b	46.5 a

A: Aroma, T: Taste, M: Mouthfeel

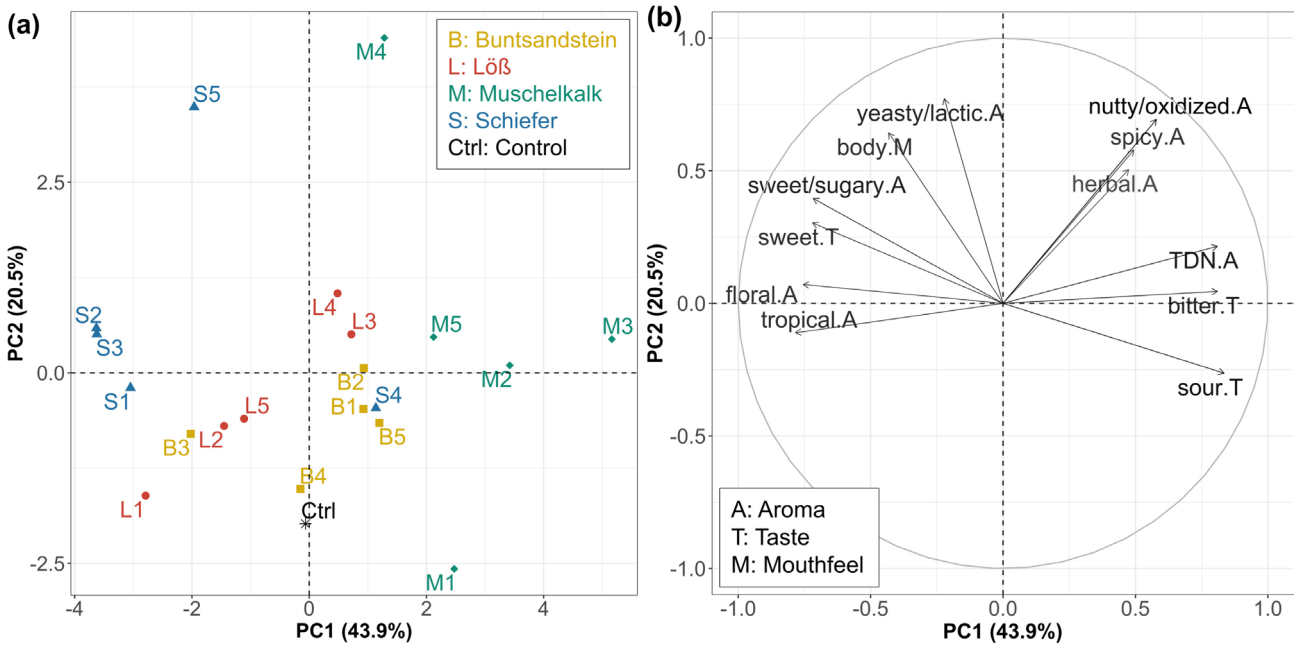


FIGURE 1. Scores (a) and loadings (b) from principal component analysis of wines in session 1 (uninformed tastings), using the attributes that differed significantly among soil types (a = 0.05).

oxidised and *bitter*, as well as the least *sweet*, though these were attributes shared with *Löß*, *Buntsandstein*, and the control, respectively. On the other hand, *Schiefer* wines were the least *sour*; they were also rated most highly along with *Löß* for *sweet/sugary* aroma and *sweet* taste. Wines from *Buntsandstein* and *Löß*, as well as the control, always shared groupings with other soil types.

2. Session 2: Informed tastings

Results from MANOVA on the data from session 2 indicate significant differences among soil types and among wines within each soil type. Neither *replicate* nor the *soil*replicate* interaction were significant sources of variance, suggesting judges evaluated each of the labelled controls repeatably (n = 2 for each soil type). According to ANOVA, several attributes not found to significantly differ among soils in session 1 were then significantly different in session 2: *apple/pear*, *citrus*, *peach/apricot*, *fresh/grassy*, *vegetal*, *reduced*, *chalky*, *earthy*, *flinty*, *marine*, *salty*, and *alcohol* (Table 3). On the other hand, *soil* was no longer a significant source of variance for *spicy* (p = 0.387), *nutty/oxidised* (0.145), and *TDN* (0.787).

TABLE 3. Marginal means for attributes that differed significantly among soil types in session 2 (informed tastings), indicated by different lowercase letters across rows (a = 0.05).

	Buntsandstein	Löß	Muschelkalk	Schiefer
apple/pear.A	29.1 b	28.0 b	21.5 a	27.8 b
citrus.A	34.8 b	28.4 a	29.8 ab	35.3 b
peach/apricot.A	30.8 b	25.7 ab	24.5 a	30.6 ab
tropical.A	19.5 b	16.4 ab	12.0 a	19.0 b
sweet/sugary.A	10.2 ab	13.2 b	8.4 a	14.2 b
floral.A	22.5 b	18.4 ab	15.5 a	23.8 b
fresh/grassy.A	8.9 ab	5.2 a	10.9 b	9.8 b
vegetal.A	7.3 a	8.2 ab	12.2 b	6.9 a
herbal.A	15.5 ab	13.8 a	18.4 ab	20.1 b
yeasty/lactic.A	5.8 ab	4.1 a	5.9 ab	8.3 b
reduced.A	10.6 ab	8.3 a	10.7 ab	12.1 b
chalky.A	4.3 a	5.6 a	11.5 b	4.7 a
earthy.A	7.7 a	11.5 b	7.1 a	6.7 a
flinty.A	11.9 ab	9.1 a	15.1 b	21.7 c
marine.A	1.4 a	2.2 ab	4.5 b	3.2 ab
sweet.T	41.0 b	42.1 b	32.6 a	43.4 b
sour.T	47.2 ab	42.9 a	48.9 b	46.4 ab
salty.T	23.0 a	24.3 ab	28.4 bc	29.6 c
bitter.T	21.8 ab	22.2 ab	24.5 b	18.6 a
alcohol.M	55.6 b	56.2 b	57.4 b	48.2 a
body.M	52.6 b	55.1 b	54.0 b	48.5 a

A: Aroma, T: Taste, M: Mouthfeel.

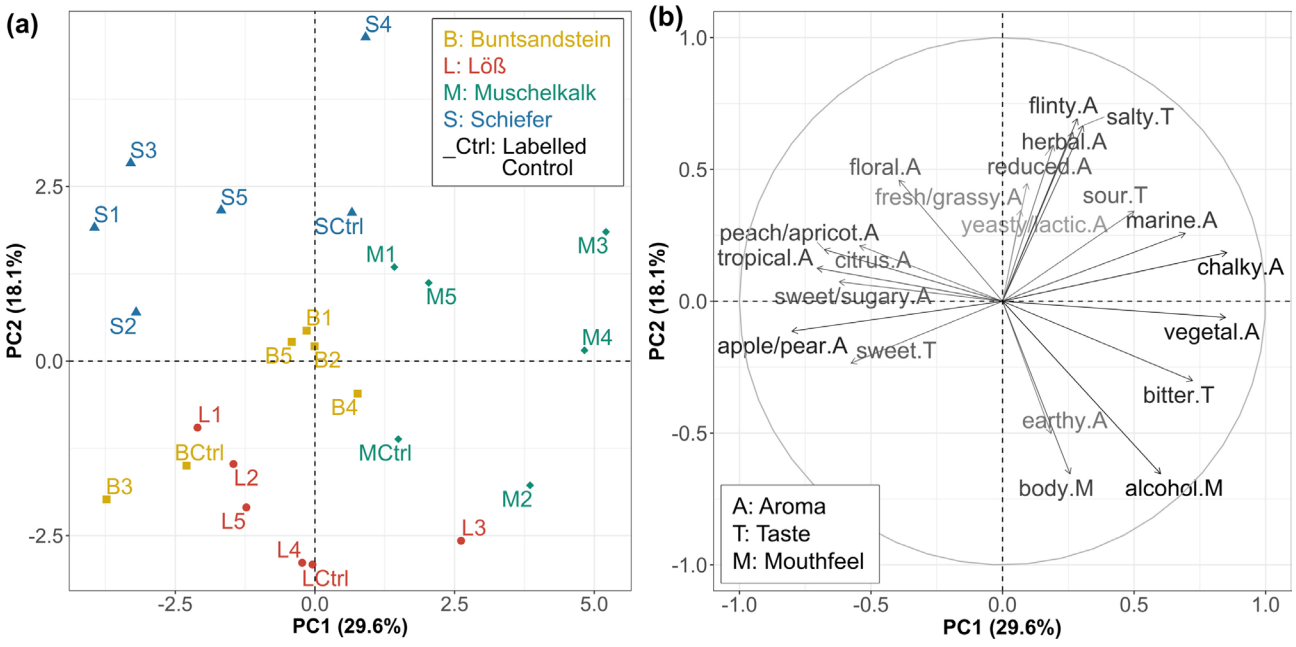


FIGURE 2. Scores (a) and loadings (b) from principal component analysis of wines in session 2 (informed tastings), using the attributes that differed significantly among soil types (a = 0.05).

In the PCA score plot (Figure 2a), wines from *Muschelkalk* can be found in the positive direction of PC1 (29.6 % of the variance), while most wines from the other soil types tend toward the negative direction. The positioning of the *Muschelkalk* wines indicates they were rated highly for *chalky*, *vegetal*, *marine*, and *bitter*, but low for various sweet, fruity flavours (Figure 2b). The *Schiefer*, *Buntsandstein*, and *Löß* wines are generally separated along PC2 (18.1 % of variance) from top to bottom. Their locations in the score plot suggest the *Schiefer* and *Löß* wines were perceived as opposites: *Schiefer* wines were characterised by more *tropical, floral*, and *flinty* aromas, whereas *Löß* wines were higher in *earthy* aroma, *body*, and *alcohol*. Furthermore, the *Löß* wines were generally lacking in several other attributes driving PC2: *herbal*, *reduced*, *fresh/grassy*, and *salty*. Wine B3 and the control labelled "*Buntsandstein*" (BCtrl) were perceived as being particularly *sweet* with *apple/pear* aroma, though the other *Buntsandstein* wines lie much closer to the centre of the plot. BCtrl and the other controls labelled "*Löß*," "*Muschelkalk*," and "*Schiefer*" (LCtrl, MCtrl, and SCtrl, respectively) are well separated from each other and are generally found in close proximity to the other wines from their respective soil types.

Wines from *Löß*, *Muschelkalk*, and *Schiefer* had at least one distinguishing attribute, while those from *Buntsandstein* always shared groupings with other soil types (Table 3). The *Löß* wines were rated as the most *earthy*, whereas *Muschelkalk* wines were highest in *chalky* aroma, and lowest in *apple/pear* aroma and *sweet* taste. *Schiefer* wines were clearly perceived as being the most *flinty* and having the least *alcohol* and *body*.

3. Changes between sessions: "Delta" values

According to MANOVA on Δ values, *soil* was a significant source of variance, while *wine* nested within *soil* was not, indicating the shifts in perception between sessions were soil-dependent, but not wine-dependent. Despite the wines differing significantly within each soil type when the sessions are considered separately, results here from Δ analysis suggest perception changed collectively, in a similar manner for all wines from each soil type. It is particularly worth noting that Δ values for the labelled controls did not differ significantly from those of the other wines from their respective soil types.

Most of the Δ values for which *soil* was a significant source of variance according to ANOVA belong to attributes that were significant in only one of the two sessions. As seen in the PCA biplot (Figure 3), PC1 (52.3 % of variance) is driven mainly by differences between *Löß* and *Muschelkalk* Δ values, with *Buntsandstein* in the middle. Perception of *spicy*, *earthy*, and *nutty/oxidised* tended to increase from session 1 to session 2 for the *Löß* wines, while *fresh/grassy* decreased. In the other direction of PC1, *chalky* increased for *Muschelkalk* wines, while *TDN* decreased. Differences between *Schiefer* wines and the other soil types appear to drive PC2 (41.4 % of variance). In the positive direction, ratings for *flinty*, *sour*, and *salty* increased for *Schiefer* wines while decreasing for the others, and in the negative direction, *alcohol* and *body* decreased for *Schiefer* wines while increasing for the others.

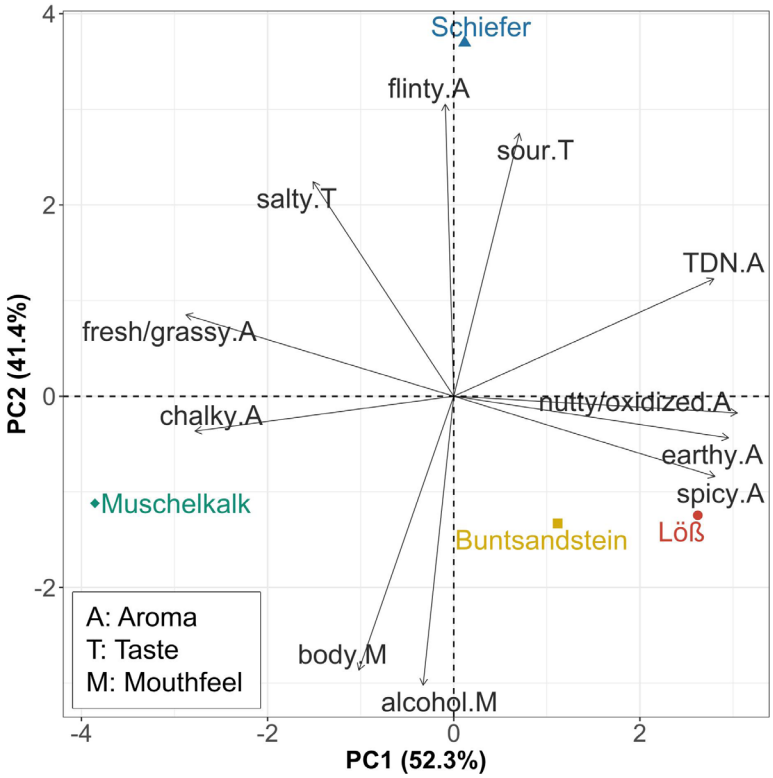


FIGURE 3. Biplot from principal component analysis of the changes in ratings from session 1 to session 2 (Δ values), using the attributes for which Δ values differed significantly among soil types (α = 0.05).

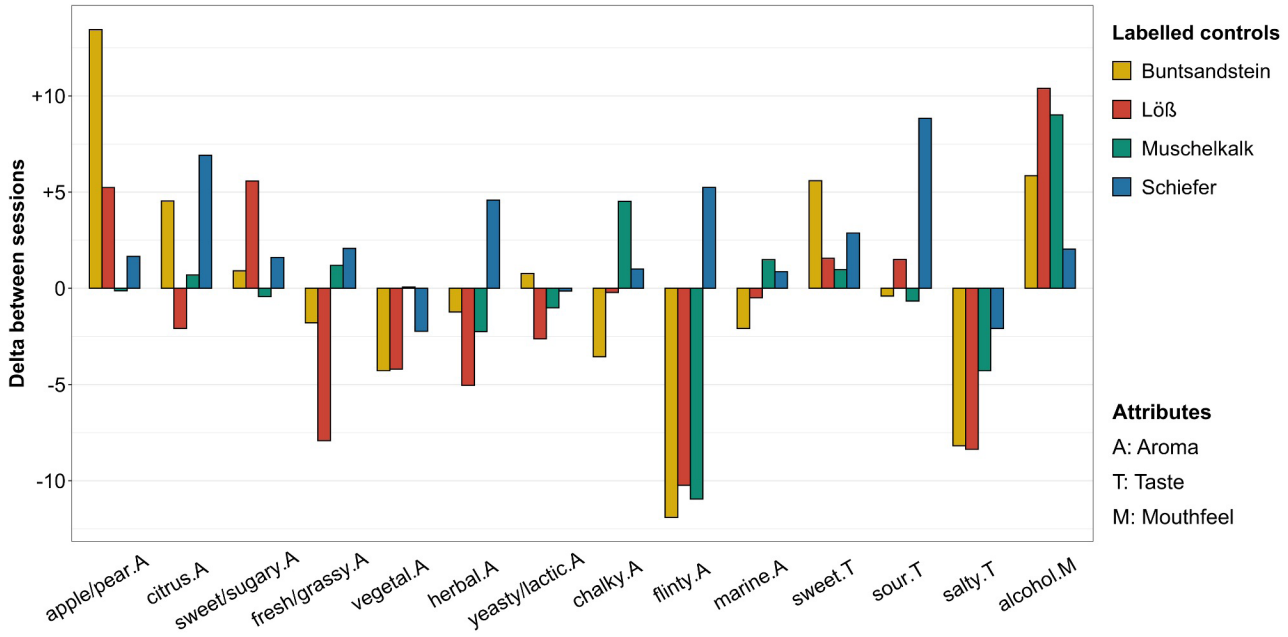


FIGURE 4. Changes in ratings from session 1 to session 2 (Δ values) for the control wine labelled with the four soil types, for attributes whose Δ values differed significantly among soil types (a = 0.05).

Differences in Δ values for these attributes among the labelled controls clearly demonstrate how the perception of even a single wine can be altered significantly by the cue provided during sensory evaluation (Figure 4). Perception of *fresh/grassy* decreased significantly from session 1 to session 2 for the LCtrl, *chalky* increased for the MCtrl, while *sour* increased for the SCtrl. Additionally, the SCtrl exhibited a distinct increase in *flinty* aroma, which decreased significantly for all three of the other controls.

DISCUSSION

1. Baseline differences among soil types

The purpose of our study was to determine the influence that specifying soil types would have on sensory perception, though the results from the uninformed tastings in session 1 warrant discussion. Even without soil type cues, our judges identified what appeared to be soil type-dependent differences among the wines. In particular, wines from *Muschelkalk* were higher in *TDN*, *nutty/oxidised*, *spicy*, and *herbal* aromas, as well as *sour* and *bitter* taste, while wines from *Schiefer* were higher in *tropical*, *floral*, *sweet/sugary* aromas, and *sweet* taste (Table 2, Figure 1). Several previous studies have also observed sensory differences among Riesling wines from different soil types (Löhnertz *et al.*, 2008; Douglas *et al.*, 2001; Bauer *et al.*, 2011), though the exact nature of these differences varies significantly from study to study. For example, in contrast to our findings, Bauer *et al.* (2011) found wines from slate and sandstone (presumably corresponding to our *Schiefer* and *Buntsandstein*, respectively) to be quite similar, exhibiting relatively high levels of *minerality*, *box tree*, and *grassy/cucumber* aromas, while wines from limestone (corresponding to *Muschelkalk*) were characterised by *mango/passion fruit* and *peach/apricot* aromas. Despite trends found within each study, differences among studies are apparent, not only due to different sensory evaluation methodologies but also due to variability in environmental parameters other than soil type. To the best of our knowledge, only one study to date has attempted to control for this variability, by moving Silvaner vines from seven different soil types in lysimeters to a single location and subsequently finding no significant differences in flavour among the wines produced (Wahl, 1988; Bader and Wahl, 1996).

No mechanisms have been established by which particular vineyard soil types could influence the formation of compounds responsible for differences in wine flavour. As described recently by van Leeuwen *et al.* (2020) in their extensive review of terroir and aroma, the appearance of these compounds in wine is instead largely dependent on other aspects of a physical environment to which soil is inextricably linked. All soil types cannot exist everywhere and are instead necessarily localised to certain places, each with their own climate, topography, etc. For example, water deficit conditions, particularly in vineyards on steep slopes with low water-holding capacity, can increase concentrations of volatile thiols and terpenes (Peyrot des Gaschons *et al.*, 2005; Savoi *et al.*, 2016; van Leeuwen *et al.*, 2020), compounds responsible for the *tropical*, *floral*, and *sweet/sugary* aromas perceived here in the wines from *Schiefer*. Because this soil type is found almost exclusively in the Mosel and Nahe winegrowing regions of Germany, known for their steep, stony vineyards, it cannot be said whether these aromas should be attributed to the *Schiefer* soil type or the inherent drainage of these vineyards' slopes.

Rather than focusing on differences between soil types, the variability among wines within each soil type should be considered, as well as the overlap between them (Figure 1). Having studied Riesling from several vineyard designations in the Rheingau region of Germany, each with homogenous soil, Fischer *et al.* (1999) observed that vintage and the individual estates producing wine from these vineyards had significantly greater effects on wine flavour than the sites themselves. These findings highlight the multifactorial complexity of terroir, and soil typing can provide only an incomplete understanding of how wine flavour is derived. Nonetheless, the precise nature and magnitude of soil's contribution remains an open avenue for continued investigation. Future research could set aside soil type, perhaps as nothing more than a given name, and focus instead on measurable properties such as texture, structure, porosity, solum or rooting depth, heat and water retention, etc., which could influence grape development and the sensory properties of the resultant wine.

2. Soil-type cue-dependent changes in perception

More descriptors were used to differentiate among soil types in session 2 (Table 3) than in session 1 (Table 2), several of which are notably often used to express minerality: *flinty*, *chalky*, *marine*, *earthy*, and *salty*. On one hand, it is possible the soil type cues during session 2 heightened our judges' sensitivity to certain flavours, prompting more focused sensory evaluation (Hughson and Boakes, 2001). On the other, however, given the duration of the study and the number of wines evaluated, fatigue might have led judges to become increasingly reliant on semantic or conceptual associations, resulting in "false positives" (Hughson and Boakes, 2002). During their investigation of minerality in Burgundian Chardonnay, Ballester *et al.* (2013) observed a similar phenomenon: during a free-sorting task, panellists tended not to use minerality-related descriptors, and only did so when explicitly asked to assess minerality. The notion of objectivity in sensory perception remains a topic of continued discussion (Nguyen and Durner, 2023), and investigations into both the chemical and psychosocial/cultural bases of minerality in wine are ongoing (Deneulin *et al.*, 2016; Rodrigues *et al.*, 2017).

Regardless of whether such flavours are a "chemical reality or cultural construct" (Parr *et al.*, 2016), results from session 2 indicate that soil type, provided as an extrinsic informational cue, can influence the perception of German Riesling. Several previous studies on wine tasters' biases and expectations have similarly compared the results from sensory evaluations with and without the provision of certain information, such as critic scores (Siegrist and Cousin, 2009), price and grape variety (Peterson, 2014), and blend composition (Boncinelli *et al.*, 2016). Expectations arise from previous knowledge or experience with a product, after which extrinsic cues can lead tasters to believe the product will exhibit certain sensory properties (Deliza and MacFie, 1996; Brochet and Morrot, 1999). According to the assimilation-contrast theory, if the discrepancy between expectation and perception is not so large that contrast occurs, assimilation will shift perception to align it with expectations (Anderson, 1973).

Working "backwards" through this model, shifts in perception thus indicate underlying expectations and allow us to infer the knowledge or experience that shaped them. Differences in intensity ratings suggest our judges shared distinct concepts for Rieslings from *Buntsandstein*, *Löß*, *Muschelkalk*, and *Schiefer* (Table 3, Figure 2). This is further evidenced by the soil type-dependent Δ values calculated between sessions (Figure 3), particularly for the single control wine merely labelled with the different soil types (Figure 4).

Löß (loess) is a silty sediment formed by the accumulation of wind-blown dust (Frechen, 2011), and is considered a rich and fertile soil of great importance to agriculture (Catt, 2001). Knowing this might explain the relatively high ratings judges gave *Löß* wines for *earthy*, *body*, and *alcohol*, as well as the lower ratings for *fresh/grassy* and *salty*. The positive Δ values for *spicy* and *nutty/oxidised* might also be attributed to a conceptual understanding of *Löß* and its properties.

Muschelkalk (shell-bearing limestone) refers to layers of calcareous sediment often containing the fossilised remains of various ocean-dwelling invertebrates (Aigner, 1982; Sommaruga *et al.*, 2017), which would explain the induced perception of certain attributes, particularly *chalky* and *marine*. It should be noted the German descriptor *kreidig* used for this study (translated here as "chalky") refers to blackboard chalk and not directly to limestone (*Kalk)*, to avoid such an obvious association, which apparently occurred anyway. Explaining the inter-session decrease in perceived *TDN* among the *Muschelkalk* wines is less straightforward. Often found in Riesling wine made from grapes exposed to high temperatures and excessive sunlight (Kwasniewski *et al.*, 2010; Szmania *et al.*, 2023), the kerosene- or petrol-like aroma of TDN (1,1,6-trimethyl-1,2-dihydronaphthalene) can be categorised as empyreumatic (Ferreira *et al.*, 2022), and thus perhaps dissonant with a cold, oceanic mental representation of *Muschelkalk*.

The association of *flinty* aroma with *Schiefer* (slate) is rather interesting, given flint and slate are entirely different types of rock. It could be that slate is a particularly popular example of soil type brought up in discussions of minerality, for which *flinty* is often an associated sensory descriptor. More figurative terms such as "sharp" or "lean" are also commonly used to express minerality (Maltman *et al.*, 2013), reflected here perhaps in the *Schiefer* wines' positive Δ values for *sour* and *salty*, and negative Δ values for *alcohol* and *body*.

Conceptions of *Löß*, *Muschelkalk*, and *Schiefer* wines appear to be well-defined and differentiated, thus these soil types might be considered relatively valuable from a marketing perspective. On the other hand, should *Buntsandstein* (coloured sandstone) appear on bottle labels, etc., the sensory properties to be expected are less obvious. While results here suggest the lack of a commonly understood "image" for *Buntsandstein*, with fewer connotations and weaker associations, it is possible that other descriptors not included in our study, or the use of another methodology

such as free-choice profiling, would have allowed for better definition of wines from this soil type, and perhaps the other soil types as well. Future studies could be expanded to include other soil types seen on bottles of German Riesling; volcanic soils in particular, such as basalt or rhyolite, would likely elicit interesting expectations. The influence of soil type cues on the perception of wines from other grape varieties and regions is also worth investigating.

3. Moving forward: Consumer expectations

It should be acknowledged that our panel was composed entirely of wine experts, and such distinct expectations and biases during sensory evaluation would likely not have been apparent with nonexpert consumers. In studies of wine typicity, the reference group used to determine the distinguishing characteristics of a given class/category of wines normally comprises key stakeholders, such as wine producers, merchants, and regulatory agents, as they can forgo time-consuming training (Ballester *et al.*, 2008; Barton *et al.*, 2020) and are best capable of reporting expectations (Leriche *et al.*, 2020; Souza Gonzaga *et al.*, 2021). Moreover, central to our investigation was a reliance on experts' susceptibility to bias, given their cognitive approach to evaluating wine often allows the "top-down" application of prior knowledge to override "bottom-up" sensory perception (Spence and Wang, 2019; Spence, 2020). Nonetheless, it is possible that a wider pool of consumers, despite their lack of expertise, might have their own preconceptions of Rieslings from different soils (Deneulin *et al.*, 2016), thus an additional investigation into the response of consumers to wine soil typing may be warranted.

Consumer expectations can also be managed, perhaps using the findings here as a starting point. It cannot be said whether the effects observed were those intended by the producers when they chose to provide soil type information for their wines, nor whether these changes to sensory perception should be considered positive or negative. Therefore, it remains up to the discretion of industry members how the complexity of terroir might be distilled, and the role of soil highlighted when communicating with consumers, to set the "correct" expectations and ensure the desired flavour profile is not only perceived but appreciated.

CONCLUSION

In their review of the many factors governing grape and wine quality, Jackson and Lombard (1993) once commented, "Despite its complexity, the concept of terroir is a valuable one. The reductionist might find difficulty in appreciating its value for scientific analysis, but… the effects are real." There is clearly a tremendous range of flavours possible in wine, as we and many others have observed, even from a single grape variety, and research indeed continues to better understand the source of this variance, more clearly define terroir, and disentangle the effects of its many components. Yet soil remains a particularly potent aspect of terroir, one whose influence seems to reach beyond physical or chemical reality.

Our investigation has revealed that the mere mention of wine soil types as an informational cue during the evaluation of German Riesling can significantly influence sensory perception. Changes in ratings were soil type cue-dependent, suggesting our panel of industry professionals held distinct *a priori* conceptions for each soil, which differentially shaped their expectations and consequently primed them to perceive wines of each soil type differently. Even the perception of the control wine, a composite of all the other Rieslings in this study, changed significantly depending on which cue accompanied it. Such biasing is presumably contingent on some level of expertise or previous knowledge of the different soils, thus further work is needed to determine whether nonexpert consumers would be similarly influenced. Although perhaps an oversimplification of *terroir*, specifying soil types can nonetheless be a valuable strategy in wine marketing. For this to be effective, however, a clear "image" of each soil type must first be communicated to consumers to ensure their expectations yield the desired sensory experience.

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