Influence of sustainability programs on fungicide stewardship practices in Pacific Northwest United States vineyards

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1 Introduction

Fungicide use is a requirement for the economic survival of United States (US) grape growers. It has been estimated that approximately 95% of grape yield can be attributed to fungicide-based disease management (Gianessi and Reigner, 2006). The yearly management of powdery mildew alone requires an extensive fungicide spray program (Gadoury *et al*., 2012) that can amount to as much as 37% gross value of production (Sambucci *et al*., 2014) due in part to the current lack of powdery mildew resistance in popular *V. vinifera* cultivars. In addition, based on California economic studies, grape powdery mildew management accounted for 89% of California restricted pesticide applications (Sambucci *et al.*, 2019).

In the US, fungicide resistance in *E. necator* was first described in the 1980s (benomyl in New York) (Pearson and Taschenberg 1980). To date, there have been reports of grape powdery mildew resistant to quinone outside inhibitors (QoI; FRAC 11) (Baudoin *et al*., 2008, Miles *et al.*, 2012), demethylase inhibitors (DMI; FRAC 3) (Gubler *et al*., 1996, Erickson and Wilcox, 1997), and quinoxyfen (FRAC 13) (Wilcox and Riegel, 2012) in the US and additional reports of succinate dehydrogenase inhibitors (SDHI; FRAC 7) (Graf, 2018) and benzophenone fungicides (FRAC U08) (Kunova *et al*., 2016) resistance in Europe. This growing issue of resistance constricts the chemical toolbox available to US grape growers. Additionally, novel active ingredients coming to the market are rarer than in previous decades with an increase cost of getting products to market (Fisher *et al.*, 2018, McDougall, 2016).

With the expansion of fungicide resistance, there is a need to conserve the efficacy of available and future products. Fungicide stewardship is rooted in the use of practices that are assumed to mitigate or prevent the selection of fungicide resistance. These practices include: maintaining label-indicated application intervals, mixing active ingredients that target the same pathogen, and limiting the total use (or repeated use) of an active ingredient (van den Bosch *et al*., 2014). US grape growers are aware of the importance of these practices (Oliver *et al*., 2021), which suggests they might also be actively using these practices in their own spray decisions.

In the US wine industry, the adherence to regionally curated sustainability certifications is on the rise. Select western US examples of these programs are listed in Table 1. These programs are separate from the federally regulated (United States Department of Agriculture) Organic Certification program. In contrast to the federal Organic program, the regional sustainability certification programs are all independently managed and operated. These programs are generally more flexible than the federal organic program in their allowed chemicals, however, they still have their own individual product choice constraints and limitations. These constraints are typically complemented by a list of allowable pesticides (See websites listed in Table 1). The level of product restriction by these organizations is variable, from flexible options in Lodi Rules, to defined restrictions in the Low Input Viticulture and Enology (LIVE) program.

Program Name	State of Origin	Website
California Sustainable Winegrowing Alliance	California	https://www.sustainablewinegrowing.org/
LODI Rules	California	https://www.lodigrowers.com/
Napa Green	California	https://napagreen.org/
Sustainability in Practice (SIP)	California	https://www.sipcertified.org/
Low Input Viticulture and Enology (LIVE)	Oregon	https://livecertified.org/
Salmon Safe	Oregon	https://salmonsafe.org/
Washington Sustainable	Washington	https://www.washingtonwine.org/washington-sustainable/

Table 1: Examples of wine grape sustainability programs offered in select regions of the United States. Many programs are certified through audits. Processors purchasing the fruit can include the program logo on the final product. Some provide their own marketing to increase public awareness of their programs.

2 Purpose of presented study

The goal of the study presented here was to investigate how actual spray choices (through spray application records) may be influencing resistance selection. In this specific study, we focus on the influences of choice constraints, such as active ingredient availability and/or application rate, that can occur when participating in a regional sustainability certification program. Can these programs be inadvertently forcing growers to participate in practices that are implicated in applying selection pressure for the development of fungicide resistance?

3 Region of focus

This study focused on growers in the states of Washington and Oregon, located in north-western US. Washington and Oregon are the second and third largest wine producers in the US (USDA-NASS, 2019), respectively. In Washington, most

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wine grapes are grown east of the Cascade Mountain range. This area is classified as an arid steppe climate, with an average in-season (Apr. 1 to Oct. 31) temperatures of 11-22 °C, with a growing degree day (base 10°C) accumulation for the same time period of 1472. Annual precipitation is 20 cm, with 7 cm falling in the growing season (WRCC, 2021). In Oregon, most wine grapes are grown in the Willamette Valley, which has a maritime climate with average in-season temperatures of 10-19 °C, and a growing degree day accumulation of 1204. Annual rainfall averages 107 cm, with 36 cm falling in the growing season (WRCC, 2021). Despite these varying climates and differences in disease pressure, powdery mildew is still the primary fungal disease requiring annual in-season intervention.

4 Record collection

The FRAME network team (framenetworks.wsu.edu) solicited spray records from Oregon and Washington wine grape growers. Records included information such as: application date, product applied, product rate, and acknowledgement of whether they participated in a sustainability certification program. Additional information collected (but not required), was application acreage, spray delivery volume, and results of FRAC 11 resistance testing. Records were submitted either directly to FRAME networks personnel or anonymously through grower group collaborators. Those who chose to participate were provided a project description and privacy statements. A total of 26 vineyards provided records (13 from Oregon, 13 from Washington). These records spanned from 2016 to 2019 and all used synthetic fungicides and represent conventional production, and LIVE certification (Table 1). After receipt, the records were anonymized for analysis. Records were then compiled and cleaned in Microsoft Excel for consistency. Basic statistical analysis was completed with R (v4.1.1 “Kick Things”, Vienna, Austria) in R studio (v2021.09, “Ghost Orchid”, Boston, MA) using the package “tidyverse, 1.3.1” (Wickham *et al*., 2019).

5 Results

Of the 26 vineyards supplying records, 12 adhered to conventional production practices, while 14 adhered to LIVE practices. Between 2016 to 2019, in conventional programs, there was an average of 6 fungicide applications, with a range of 3 to 10 applications. In LIVE programs, there was an average of 9 fungicide applications with a range of 6 to 14 applications.

Products used. Between 2016 to 2019, growers conventionally managing their vineyards used products with eleven unique FRAC codes, including nine groups associated moderate to high resistance development risk, and two products associated with lower risk groups (Fig. 1). Low risk groups include: NC (not classified), M (multi-site inhibitors), BM (biologicals with multiple modes), and P (host plant defence inducers. For this study, M, MB, and P are grouped with NC, unless otherwise stated. For the same time period, growers adhering to LIVE used products with fourteen unique FRAC codes, including ten groups associated with moderate to high resistance risk and four associated with lower risk groups (Fig 1.). Three of the moderate to high-risk groups (FRAC 2, 11, and 19) were only applied in 2019 (Fig. 1).

In both conventional and LIVE programs, sulfur (FRAC M02) was the most commonly applied active ingredient. For conventional programs, FRAC 3 (DMI) was 20% and FRAC 13 was 11% of total applications. In LIVE programs, oil (FRAC NC) was 12% and both FRAC 13 and U06 were 11% of applications (Fig. 1).

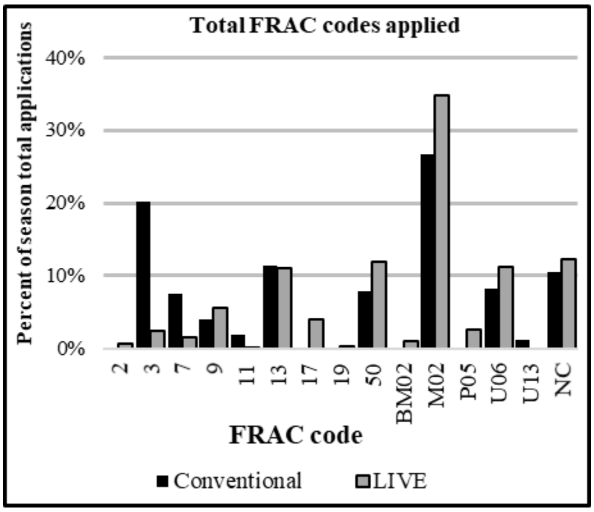

Figure 1: A subset of the total FRAC codes applied in both conventional and LIVE programs in Oregon and Washington states between 2016 to 2019.

In conventional programs, there was a reduction in FRAC 3, 11, and 13 use between 2016 to 2019 (Fig. 2). The rate of reduction in FRAC 3 averaged 4 percentage points a year, going from 26% to 16% of total applications by 2019. FRAC 11 decreased from 4% of total applications in 2016 and 2017 to no applications in 2018 and 2019. Finally, the rate of FRAC 13 use decreased the least, dropping from 13% to 9% (Fig. 2). During that same time period, there was an increase in FRAC 7, U06, and U13 use (Fig. 2). FRAC 7 increased from 3% to 9%, FRAC U06 from 4% to 10%, and FRAC increased from no applications in 2016 and 2017 to 4% in 2019 (Fig. 2).

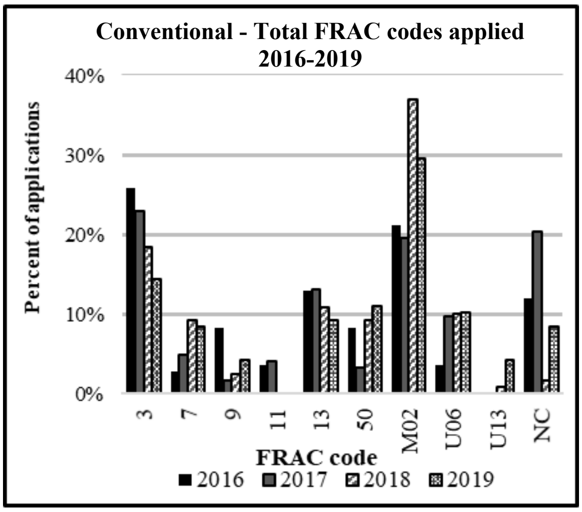

Figure 2: FRAC code application percentages from 2016 to 2019 in conventional vineyards in Oregon and Washington. N = 12 vineyards.

In LIVE programs, the use of FRAC 3 decreased between 2016 and 2019, whereas the use of FRAC 13 and 50 increased (Fig. 3). FRAC 3 decreased from 8% of total applications to 1%. FRAC 13 use decreased from 13% to 9% of total applications and FRAC 13 use increased from 7% to 11% of total applications (Fig. 3). FRAC 50 use increased from 9% to 13% of total applications from 2016 to 2019. Between 2016 and 2019, FRAC 11 products were only applied once, in one vineyard, in 2019 (Fig. 3).

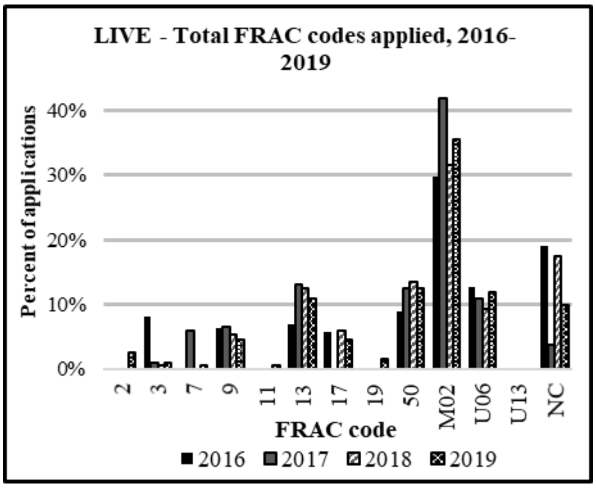

Figure 3: FRAC code application percentages from 2016 to 2019 for LIVE-certified vineyards in Oregon and Washington. N=14 vineyards.

In conventional programs, five FRAC codes were applied as the first application of the season. Three of these five codes belong moderate to high resistance risk groups and two are associated with lower risk (Fig. 4). For LIVE programs, two products were applied as the first spray: sulfur (M02) or oil (NC), both low risk products (Fig. 4).

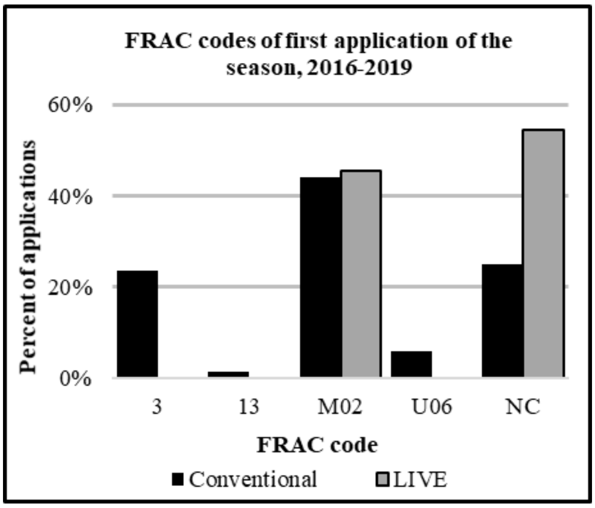

Figure 4: FRAC codes used in the first application of the season in conventional (n=12) and LIVE programs (n=14) between 2016 to 2019.

In conventional programs, there were ten different FRAC codes commonly used in the last spray application of the season; seven of those fungicide categories are considered moderate to high resistance development risk. Three were associated with lower risk groups (Fig. 5). In LIVE programs, eleven FRAC codes were commonly applied as the last spray of the season, with seven belonging to moderate to high resistance development risk groups and four associated with lower risk groups (Fig. 5).

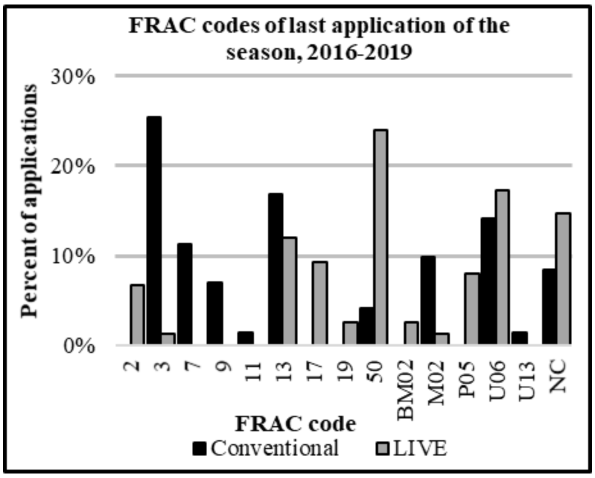

Figure 5: FRAC codes used in the last application of the season in conventional (n=12) and LIVE programs (n=14) in between 2016 to 2019.

Application intervals. The mean spray application interval was 14.6 and 14.3 days for conventional and LIVE programs, respectively. For vineyards following conventional spray approaches, there was a bimodal distribution of the application interval; while 14 days was the dominant application interval, there were also many growers who used 21-day intervals (Fig. 6). In LIVE, application intervals had a single were centred on 14 days (Fig. 6).

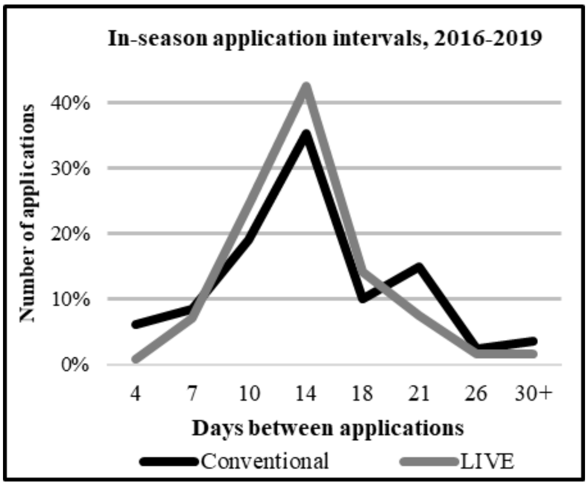

Figure 6: Days between applications (application interval) in conventional (n=12) and LIVE programs (n=14) in Oregon and Washington between 2016 to 2019.

Tank mixing. Overall, between 2016 and 2019, the percent of fungicide applications that were tank mixed increased, regardless of program style (Fig. 7). In conventional programs from 2016-2019, the percent of first spray applications that were tank mixed increased from 42% to 50% (Fig. 7) and contained four distinct tank mixes: FRAC 3+M02, FRAC 13+M02, FRAC 3+NC, FRAC U06+NC. At bloom, tank mixing increased from 33% to 67% (Fig. 7) and contained 7 distinct tank mixes: FRAC 3+M02, FRAC 13+M02, FRAC 50+M02, FRAC U06+M02, FRAC 3+NC, FRAC 13+NC, and FRAC U06+NC. Tank mixing increased from 17% to 25% in the last spray application (Fig. 7) and contained seven distinct tank mixes: FRAC 3+M02, FRAC 13+M02, FRAC 50+M02, FRAC U06+M02, FRAC 3+NC, FRAC 13+NC, and FRAC 7+U13.

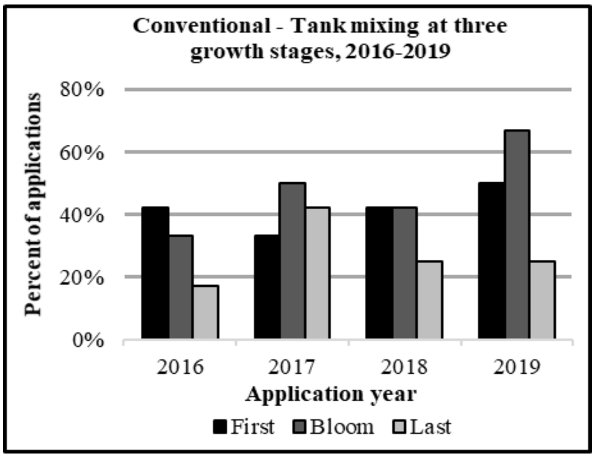

Figure 7: Tank mixing (sprays containing more than one fungicide active ingredient) in conventional programs for three application timings from 2016 to 2019.

In LIVE programs, the first spray application was not a tank mix from 2016 to 2019 (Fig. 8), and all applications were of multi-site products (FRAC M02 and NC). At bloom, tank mixing increased from 0% to 21% (Fig. 8) and contained 4 distinct tank mixes: FRAC 3+M02, FRAC 13+M02, FRAC 50+M02, and FRAC U06+M02. Tank mixing for the last application increased 8 to 71% (Fig. 8) and contained eight distinct tank mixes: FRAC 13+M02, FRAC 50+NC, FRAC 13+NC, FRAC U06+NC, FRAC BM02+NC, FRAC P06+NC, FRAC 13+2, and FRAC 50+17.

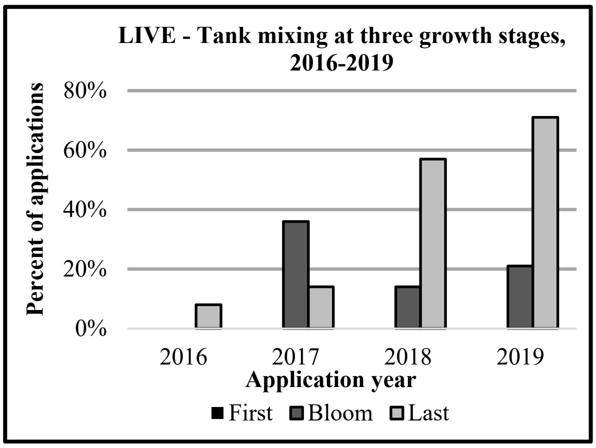

Figure 8: Tank mixing in LIVE programs for three application timings from 2016 to 2019.

6 Discussion

Overall, sulfur was the most commonly applied fungicide in the region between 2016 and 2019, regardless of whether the vineyard farmed conventionally or adhered to the LIVE sustainability certification standard. Sulfur can be used as a solo product, or as a tank-mixing partner, which is likely why it is a favoured fungicide. Growers following conventional programs applied more FRAC 3 and 7 fungicides. This is likely because the LIVE sustainability program restricts the use of FRAC 3 and 7 products to one time a year. LIVE growers are additionally limited in their FRAC 3 use, as it is not allowed during grapevine bloom, and FRAC 7 can only be applied for *Botrytis cinerea* control. Growers following the LIVE program applied more FRAC 17, 19, 50, and U06 than conventional growers. FRAC 13 was applied in similar quantities in both program styles.

Application intervals are recommendations based on an estimation of how long a chemical persists on or within a crop in effective concentrations. Despite the mean application intervals being 14.6 and 14.3 days for conventional and LIVE programs, respectively, conventional programs were more likely to use extended (21 day) intervals. If application intervals are lengthened, pathogen populations can be exposed to sublethal or uneven distributions of the product, potentially leading to the selection of fungicide resistance. Additional efforts to define actual duration of efficacy is needed to improve fungicide stewardship recommendations.

Tank mixing for fungicide stewardship is the application of two or more FRAC codes at the same time, for the same target pathogen. Generally, tank mixing has increased over the years in all vineyards in this study. Further exploration as to whether tank mixes are applied as a fungicide premix, or being mixed on-farm by the applicator, may help develop improved recommendations for fungicide stewardship.

7 Conclusions

The question of whether or not the product restrictions decreed by certified sustainable programs could hinder fungicide stewardship practices is a difficult one. On average, vineyards that were farmed conventionally had fewer overall fungicide applications in a year and fewer applications could mean fewer resistance selection events. LIVE-certified vineyards, even though they had more fungicide applications, used lower-resistance risk products with fewer extended intervals. This suggests that presentation of which fungicide stewardship principles growers should focus on needs to be tailored to individual groups.

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