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Pest prevention, risk, and risk management: The case of *Drosophila suzukii*

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Abstract

Pest prevention can play an important role in reducing pest pressure and pesticide use. Yet its adoption remains suboptimal. We develop a theoretical model to analyze the circumstances that favor or hinder the uptake of preventive measures against pests, and test the derived hypotheses using an empirical application of Swiss grapevine producers' decisions on preventive measures against *Drosophila suzukii*. We show that higher risk aversion hinders farmers' prevention efforts. Furthermore, lower general background risk, characterized by the use of crop insurance, decreases pest prevention. We discuss the implications for supporting policy goals of managing pest pressure and reducing pesticide use.

KEYWORDS

integrated pest management, pest prevention, risk management, risk preference

JEL CLASSIFICATION

D81, Q12, Q57

1 | INTRODUCTION

Plant protection is the basis for the production of high-quality food in adequate quantities (e.g., Oerke, 2006; Popp et al., 2013; Savary et al., 2019). Yet, if plant protection is based on the use of pesticides, it entails negative effects on the environment and human health (e.g., Damalas & Eleftherohorinos, 2011; Kudsk et al., 2018; Landrigan et al., 2018; Tang et al., 2021). Reducing the use of pesticides without restricting food production is thus on the top of current policy and industry agendas (e.g., Möhring et al., 2020). A key strategy to achieve pesticide reduction is to rely on integrated pest management principles that foster the use of preventive, nonchemical strategies

(Barzman et al., 2015; Olson & Roy, 2005). This reduces potential pest pressure and thus reduces pesticide use (Waterfield & Zilberman, 2012). However, the uptake of these preventive nonchemical strategies is below the social optimum and on the top of policy agendas (see e.g., Fan et al., 2020; Parsa et al., 2014). Recent policy decisions to massively reduce pesticide use and risk in Europe emphasize relevance of this issue. For example, the "Farm to Fork" strategy of European Union aims to reduce pesticide use and risk by 50% by 2030 (Schebesta & Candel, 2020); Switzerland even aims to reach these goals by 2027 (Finger, 2021). Preventive strategies are a key pathway to massively reduce pesticide use and risk, while maintaining food production.

This paper offers theoretical and empirical insights in farmers' pest prevention decisions. We develop a theoretical model to analyze which conditions and farm and farmers' characteristics favor or hinder the uptake of preventive measures. Next, we test hypotheses from the theoretical model using an empirical application of Swiss grapevine producers' decisions to use preventive measures in response to spotted wing drosophila (*Drosophila suzukii*), a major invasive pest of soft fruits in the Americas and Europe (e.g., Asplen et al., 2015; Fan et al., 2020).

Previous literature has addressed the dynamics and intertemporal interdependencies of pest management. For instance, Skevas et al. (2013) show that there are intertemporal spillovers of pesticide application on future production and farmers consider this in a multiyear horizon on pesticide use decisions. Fan et al. (2020) show that producers may not adopt monitoring-based management, an integrated pest management practice, to control spotted wing drosophila, but often rely on calendar-based insecticide spray strategies if the perceived trapping efficiency is too low. With a focus on pest prevention in agriculture, Kan et al. (2013) find that installing barn owl nesting boxes can be a profitable preventive measure for rodent control in agriculture, but also show that stricter regulations on rodent control using rodenticides are required to incentivize large scale use of prevention. Moreover, preventive efforts have been related to the role of extension and information (e.g., Tambo & Matimelo, 2021; Wuepper et al., 2021) as well as a wide range of farm-, farmer- and institutional characteristics (see e.g., Lefebvre et al., 2015, for a review). Especially, farmers' perceptions of costs, benefits, risks, as well as preferences, for example, toward risk, have shown to determine preventive efforts. A key characteristic of pest prevention is that prevention needs high upfront investment and that the economic return of this action is highly uncertain. For example, Finnoff et al. (2007) show, in a nonagricultural context, that risk and risk preferences matter for optimal prevention choices. More specifically, they show that the prevention of invasive species may not be attractive for risk averse decision makers because control is a safer choice than prevention, due to the relatively lower uncertainty in its efficacy. The evidence, however, remains in the theoretical domain.

We here contribute a new perspective to the literature on pest prevention in agriculture by combining a theoretical and an empirical analysis of the use of preventive measures in response to spotted wing drosophila (*D. suzukii*, e.g., Fan et al., 2020). We develop a coherent framework to combine theory with an empirical application relying on farm-level data over multiple periods of farmers' preventive action and preferences. More specifically, we develop a model on farmers' optimal prevention efforts capturing the dynamics of pest pressure and pest prevention as well as pest control using insecticides. We account for different sources of risks and risk preferences. Hypotheses derived from the theoretical model are tested empirically using survey data on prevention in Swiss grapevine production in response to spotted wing drosophila. Infestation can be devastating as spotted wing drosophila affects ripe, healthy fruits and infested fruits become unmarketable. Zero tolerance policies especially for fresh produce market products amplify possible losses. Thus, high economic impacts of spotted wing drosophila have been reported (e.g., Bolda et al., 2010; Fan et al., 2016; Knapp, Wuepper, et al., 2021; Mazzi et al., 2017). Possible prevention strategies comprise sanitation measures as well as technical solutions such as installing insect nets (e.g., Knapp et al., 2019; Knapp, Mazzi, et al., 2021). Previous studies show that current practices in response to spotted wing drosophila often underuse preventive strategies and overuse pesticides, despite evidence that prevention strategies can effectively reduce pest population (Haye et al., 2016; Van Timmeren & Isaacs, 2013, Wiman et al., 2016).

Our results show that prevention effort increases with perceived pest pressure based on prior experience, and decreases with the cost of prevention relative to farmers' wealth. For the empirically plausible class of power utility functions, higher risk aversion, characterized by a higher value of the coefficient of absolute risk aversion, hinders farmers' prevention efforts. Furthermore, both state-dependent risk in the case of infestation and general background risk would increase a farmer's optimal level of pest prevention. We further find empirical evidence consistent with the theoretical relations in our case study of spotted wing Drosophila in Swiss wine grape cultivation. Notably, estimates from a linear probability model indicate that, controlling for other factors, farmers with crop insurance (i.e., used as proxy for experienced lower background risk) are less likely to adopt prevention measures by 19–23 percentage points compared to farmers without crop insurance.

The remainder of this paper is structured as follows. First, we develop the theoretical model that is applied to derive hypothesis for the empirical application. Second, we present the data used for the case study and third the econometric framework. Fourth, we present and discuss the results. Finally, we conclude.

2 | THEORETICAL MODEL

We here conceptualize farmers' decisions to use preventive measures as opposed to insecticide applications to manage spotted wing drosophila.[1] An investment in preventive measures is needed *before* the pest occurrence is observed. Because the pest occurrence is stochastic (i.e., occurrence and intensity of pest occurrence is not known or predictable), the returns to this investment are uncertain. To control the pest *after* pest occurrence, that is, if the infestation is observed, mainly insecticides are used.[2]

We use a two-period expected utility maximization model to conceptualize farmers prevention efforts (see e.g., Menegatti, 2007, 2009 and Courbage & Rey, 2012 for more general discussions). Our focus is laid on the optimal prevention efforts of a representative farmer, used in period 1. In the context of spotted wing drosophila these comprise the use of nets that exclude spotted wing drosophila from the fruits, various strategies to reduce habitat attractiveness for spotted wing drosophila including the pinching back of foliage, additional mowing, removal/mulching of all residuals from earlier harvests as well as the early harvest of fruits (e.g., Knapp et al., 2019; Mazzi et al., 2017). Insecticide use in period 2 only takes place if infestation is observed, that is, when pest pressure is so high that preventative measures failed to prevent infestation. Insecticide is inevitable in this situation because if untreated, *D. suzukii* causes the total loss of production and the costs of insecticide treatments are far lower than the value of the production (see e.g., Mazzi et al., 2017). Thus, insecticide use is the residual of pest pressure and prevention efforts.

Any prevention efforts e incur additional costs in period 1, for example, due to additional labor costs (e.g., for increasing sanitation measures) and/or capital (e.g., for installing nets), summarized as $C_{PE} = f(e)$. The probability for infestation to occur in period 2, Pr, depends on prevention effort chosen in period 1 and stochastic pest pressure s which is observed in period 2. Once infestation occurs, farmers can either choose to take additional pest control measures (e.g., applying pesticide), or forgo the infested harvest. We assume that all other things equal, prevention effort reduces the probability of infestation, though marginal benefit of prevention saturates: $\partial Pr/\partial e < 0$ and $\partial^2 Pr/\partial e^2 > 0$, and pest pressure increases the probability of infestation: $\partial Pr/\partial s > 0$. In the case of

[1]Other approaches used in the related literature do not account for the time lag between in the decision on prevention measures and actual damage occurrence (e.g., Finnoff et al., 2007). As we will outline below, the uncertainty regarding the pest occurrence in subsequent periods is however crucial for decision making and thus needs to be represented explicitly. Menegatti (2009) discusses more general the need to consider a two-period perspective in the analysis of prevention.

[2]See Knapp et al. (2019), for detailed descriptions of strategies used to prevent and control *Drosophila suzukii* in Switzerland. As an alternative to insecticides, a natural, stone-based repellent called Kaolin can be used to prevent large-scale damages after first infestations are observed.

infestation, farmers face expected profit reduction of C_{PC} due to cost for insecticide application and additional requirements to sort infested products. Due to the stochastic pest pressure, benefits from investment in preventive efforts are highly uncertain. In contrast, pesticide use might reflect the safer choice than prevention because the marginal benefit may be less uncertain[3] (see also Finnoff et al., 2007).

In period 1, the farmer has initial financial assets related to farming (left after buying inputs and including fixed costs) of π_1 that are reduced by costs for prevention. The additional assets received in period 2 consist of returns from crop production and are reduced by costs for pest control. We follow Menegatti (2009) and assume the von Neumann-Morgenstern utility function u to be identical for both periods and to reflect a risk averse decision maker, so that $u' > 0$ and $u'' < 0$.[4] We further assume risk prudence of the decision maker, that is, $u''' > 0$, and we will show the relevance of this assumption. As we focus on intertemporal decision that span only over some weeks and capital costs in Switzerland are close to zero, we drop the discounting of returns across periods. The resulting inter-temporal utility function that is maximized with respect to e is:

$$V(e) = u(\pi_1 - f(e)) + Pr\,(e, s)u(R - C_{PC}) + (1 - Pr\,(e, s))u(R). \tag{1}$$

We can show that for a risk averse decision maker, there is a unique utility-maximizing level of e chosen by

$$u'(\pi_1 - f(e^{\star}))f'(e^{\star}) = Pr'(e^{\star}, s)(u(R - C_{PC}) - u(R)). \tag{2}$$

We provide detailed proof in Supporting Information: Appendix A1.

The left-hand side of Equation (2) summarizes marginal costs of prevention. Marginal benefits of prevention are summarized on the right-hand side of Equation (2) and are caused by a reduction in the probability of infestation and the utility difference between the two states, that is, with and without infestation. The optimal level of e that equalizes marginal benefits and costs in this base model is denoted as $e^{\star}$.

Equation (2) reveals several relationships between prevention effort and relevant factors. One that is particular relevant to our empirical hypothesis is:

Result 1. *Prevention effort increases in pest pressure that could induce infestation.*

Proof .. See Supporting Information: Appendix A1. □

Since farmers do not observe the actual pest pressure when making decisions on pest prevention, we expect that prevention effort increases with perceived pest pressure. While pest pressure depends on growing conditions, even under similar growing conditions, the susceptibility to *D. suzukii* vary largely across grape varieties (Tonina et al., 2020). Thus it is important to separately consider the likelihood of infestation for different varieties. Within each variety, farmers may further form their perception of pest pressure based on previously observed pest occurrence and infestation on the vineyard. Thus, we expect that optimal prevention efforts are higher for more susceptible varieties and when farmers experienced greater pest pressure in a previous period.[5]

[3]Pesticide application is highly effective and takes place after pest occurrence is observed.

[4]See Iyer et al. (2020), for a recent survey on European farmers risk preferences.

[5]Equation (2) also indicates that optimal prevention efforts increase for higher fixed costs in the case of infestation C_{PC}. Thus, higher pesticide costs or higher requirements for post-processing after infestation increase prevention efforts. Reduced costs for preventive measures, C_{PE} also increases optimal prevention efforts. Furthermore, optimal prevention effort increases with higher initial assets π_1. Due to data limitations, we will not empirically test these relationships in our case study.

Apart from farming-related assets, farmers may also diversify their financial portfolio via on-farm and off-farm investment and work, which could influence their risk management decisions. See Knapp, Mazzi, et al. (2021) for a discussion.

We next investigate the role of risk preference in the farmers' choice of prevention efforts. This entails how the level of risk aversion affects the marginal cost and marginal benefit of prevention measures. From Equation (2), the relation would depend on the functional form of farmers' utility function u. We focus our investigation on the class of utility function with decreasing absolute risk aversion, which is consistent with empirical evidence of risky decisions (Friend & Blume, 1975). Note that decreasing absolute aversion also implies risk prudence, that is, $u''' > 0$. We consider a generic class of power utility: $u(x) = \frac{1-\gamma}{\gamma}(x+\alpha)^{\gamma}$, with $0 < \gamma < 1$, where x denotes the total wealth of the individual. The utility function displays increasing relative risk aversion, consistent with properties of risky decision reported in Dionne and Eeckhoudt (1985), and contains the special case of constant relative risk aversion when $\alpha = 0$. The first-order condition for utility maximization becomes:

$$(1-\gamma)(\pi - f(e) + \alpha)]^{\gamma-1} f'(e) = Pr'(e,s)\frac{1-\gamma}{\gamma}[(R - C_{PC} + \alpha)^{\gamma} - (R+\alpha)^{\gamma}]. \quad (3)$$

In Supporting Information: Appendix A2 we show that higher risk aversion, characterized by a higher value of the coefficient of absolute risk aversion (i. e. $-u''/u'$) either due to a lower value of γ or α, is associated with lower levels of optimal prevention efforts.[6] This result is consistent with findings in Finnoff et al. (2007), that more risk averse decision makers tend to use less prevention measures due to the higher uncertainty in the benefits of prevention measures compared to pesticides.

We summarize these findings in the following result:

Result 2. *Risk aversion, measured by the coefficient of absolute risk aversion, decreases the optimal prevention efforts, assuming the decision maker has decreasing absolute risk aversion.*

Next, we enrich our analysis by considering further sources of risk that farmers face when making decisions on pest prevention. More specially, we first incorporate that costs for pest control and remaining yield losses after pesticide application are uncertain. This reflects uncertainty with respect to the efficiency of pest control strategies as well as the uncertainty in the extent to which crops can be marketed even after pesticide application. This is especially relevant for our case study as we address a newly introduced pest where farmers have little experiences to build upon. Second, we account for the uncertainty of revenues, for example, due to stochastic price or yield levels.

First, accounting for uncertainty in the economic burden in case of infestation induces a state dependent risk component (Courbage & Rey, 2012), which we denote as ε_{PC} (with $E(\varepsilon_{PC}) = 0$). Due to factors such as weather conditions and other crop arrangements, stochastic pest pressure could further affect profit apart from the expected profit reduction, C_{PC}. The state dependent risk component ε_{PC} is therefore not influenced by individual efforts. The resulting new inter-temporal utility function is

$$V_1(e) = u(\pi_1 - f(e)) + Pr(e,s)E[u(R - C_{PC} + \varepsilon_{PC})] + (1 - Pr(e,s))u(R). \quad (4)$$

The first-order condition for the new utility maximization problem becomes

$$u'(\pi_1 - f(e^{**}))f'(e^{**}) = Pr'(e^{**}, s)(E[u(R - C_{PC} + \varepsilon_{PC})] - u(R)). \quad (5)$$

[6]That is, in the comparative statics, we consider cases where only one of γ and α changes at a time, and exclude simultaneous changes of both parameters.

Result 3.1. *Uncertainty with respect to pest control costs increases the optimal level of prevention effort, $e^{**} > e^*$ if the decision maker is risk averse, that is, $u'' < 0$.*

Proof .. See Supporting Information: Appendix A3. □

Thus, accounting for the uncertainty regarding the costs of pest control in period 2 increases the level of optimal prevention. Like in the case of pest pressure, uncertainty regarding the costs of pest control also depends on the variety. Furthermore, the possibility to sell the fruits even after infestation occurs reduces the uncertainty of loss in case of infestation. Thus, perfect knowledge of the implications of infestation (i.e., which strategies to use and what costs to expect) and certainty on the marketing of products even after infestation reduce optimal prevention efforts. By contrast, acknowledging the uncertainty in these respects would increase optimal prevention efforts.

Next, we consider revenues from crop production obtained in period 2 to be stochastic, for example, due to (in general) variable output prices or yield variations beyond pest-related yield fluctuations. This (general, i.e., not state-dependent) background risk ε (with $E(\varepsilon) = 0$) is introduced as follows:

$$V_2(e) = u(\pi_1 - f(e)) + \Pr(e, s)E[u(R - C_{PC} + \varepsilon)] + (1 - \Pr(e, s))E[u(R + \varepsilon)] \quad (6)$$

The optimal use of prevention measures now is implied if

$$u'(\pi_1 - f(e^{***}))f'(e^*) = Pr'(e^{***}, s)(E[u(R - C_{PC} + \varepsilon)] - E[u(R + \varepsilon)]). \quad (7)$$

Result 3.2. *Uncertainty with respect to revenues from crop production increases the optimal level of PE, $e^{***} > e^*$ if the decision maker is risk averse and prudent, that is, $u'' < 0$ and $u''' > 0$.*

Proof .. See Supporting Information: Appendix A4. □

Adding uncertainty regarding revenues from crop production increases the level of optimal prevention, given that the decision maker is prudent. Background risk in period 2 increases prevention efforts (Courbage & Rey, 2012), reflecting that a prudent decision maker aims to especially avoid low-tail income events by increasing prevention efforts (e.g., Liu & Meyer, 2012).[7] In contrast, producers with lower general background risks (e.g., by using hail nets, insurances, and diversifying income sources, etc.) shall, ceteris paribus, have lower optimal prevention efforts.

3 | CASE STUDY AND DATA

We use a case study of Swiss grapevine producers' actions against spotted wing drosophila as an empirical investigation of the relevant factors that could influence prevention effort that we discuss in our theoretical analyses. Data for the case study are based on an online survey sent to Swiss grapevine producers. The survey contains variety-specific information on measures taken to prevent or control spotted wing drosophila, as well as farmers' perceived infestation due to the pest in the corresponding year. Prevention measures include installation of insect nets (lateral insect nets,

[7]Expanding the question of prevention into a dynamic analysis and focusing on realistic representation of (downside) risk preferences, explains the partially different results than in other studies on pest prevention (e.g., Finnoff et al., 2007).

netting of specific rows with insect nets, or netting of multiple rows with insect nets), sanitation measures (e.g., removal of harvest residue, mowing/mulching, and clean harvest of every fruit), and early harvest (see Knapp et al., 2018 for detailed descriptions of the measures). In the case that infestation occurs, farmers can also choose to apply insecticides to control infestation, though insecticides are considered as the last resort for pest control for Swiss grape growers. In addition, farmers were asked to assess the overall risk due to spotted wing drosophila via their expected overall additional cost in the coming year, and expected yield loss due to spotted wing drosophila. Furthermore, the survey provides information on farm and farmer characteristics, which include their marketing strategies, off-farm activities and risk preferences.[8]

For the case study, we examine farmers' decisions regarding prevention measures against *D. suzukii* for different grape varieties. Based on the nature of the prevention measures, we further divide the measures into labor-intensive (sanitation measures and early harvest), and capital-intensive measures that involve large investments (installation of insect nets). Installation of insect nets requires an initial investment, but can be used repeatedly in subsequent periods.[9] We focus the empirical analysis on farmers' pest prevention decisions in 2018.[10] We restrict our analysis to nonorganic producers, since farmers who adopt organic production systems have different pest management options.

To develop testable hypotheses for the empirical analyses, we revisit findings from the theoretical analyses in the context of our case study. According to the discussion of Result 1, we expect prevention effort to increase in farmers' perceived pest pressure that could induce infestation, which depends on grape variety and previously experienced pest pressure. As we discuss in the previous section, pest pressure is stochastic and is observed by the farmer only after prevention decisions are made, that is, in period 2. For each grape variety, we consider farmers to base their perceived pest pressure on the pest pressure experienced in previous periods. Previous studies have shown that the susceptibility of grapes to spotted wing drosophila varies largely across varieties (Knapp et al., 2019; Linder et al., 2014; Tonina et al., 2020). Therefore, a farmer who grows multiple varieties likely form different expectations of pest pressure and likelihood of infestation for each variety, even if the vineyards are located close to each other as they belong to the same farm. Within each variety, pest pressure also depends on microclimate conditions of temperature and precipitation, and landscape conditions such as slope and soil conditions (Asplen et al., 2015). These characteristics may influence the expected pest pressure on the same grape variety across different locations. Therefore, variability in pest pressure experienced in a previous period for a given variety reflects the geographic difference in pest pressure.

To account for previously experienced pest pressure, we utilize information in the 2016 and 2017 survey on farmers' perceived infestation by *D. suzukii*, and the measures taken against it, namely prevention measures and/or insecticide. At the individual level, previously perceived infestation and previous pest control measures are correlated with prevention decision in the current period as they are driven by the same (unobserved) factors such as actual pest pressure and farmers' preferences. Thus, including these variables at the individual level as covariates in a regression would return biased estimates. To still utilize the information, and to account for the spatial heterogeneity of pest pressure, we create neighborhood averages of previous perceived infestation and pest control measures. Specifically, for each farmer's postal code location and variety, we define a “neighborhood” that includes vineyards of the same grape variety within a 10 km radius. We then calculate within the neighborhood average values of previous (from 2016 or 2017 survey)

[8]Detailed survey information is provided in Knapp et al. (2018).

[9]The duration of use for insect nets is up to 10 years (Mazzi et al., 2017).

[10]While the survey data was collected over 3 years, we restrict the sample to farmers who responded to the 2018 survey, and at least one of the 2016 and 2017 surveys (see explanation below for the use of 2016 and 2017 surveys). Supporting Information: Table A1 shows the distribution of strategies over the two surveys that farmers responded to, with farmers' choices in the 2018 survey are displayed on the right-side axis. Over the survey period (2016-2018), an increasing number of farmers chose to adopt labor-intensive prevention measures, and the opposite applies to pesticide use.

perceived infestation, prevention measure, and insecticide application for the respective variety within a 10 km radius. These neighborhood average values therefore mitigate biases due to individual-level unobserved factors such as preferences.[11]

To ensure that each vineyard has at least one neighboring vineyard of the same variety for the calculation of neighborhood averages, we further restrict the sample to the nine most grown varieties. Drawing on findings from previous studies (Knapp et al., 2019; Linder et al., 2014; Tonina et al., 2020), we group the varieties based on their susceptibility to spotted wing drosophila, which is particularly high for dark, soft-skinned grape varieties. Prevention measures were used more prevalently among grape varieties of high or medium-high susceptibility to *D. suzukii* compared to low-susceptible varieties (Table 1).

According to Result 2, higher risk aversion is associated with less prevention effort. We test this hypothesis in the context of our case study, and further explore whether the association varies across different domains of risk preference. We consider farmers' self-stated risk preferences in the domains of production, market and prices, and external financing. We measure farmers' risk preferences via Likert type contextualized self-assessment questions on their willingness to take risks in the abovementioned domains, following Dohmen et al. (2011), Weber et al. (2002), and Meuwissen et al. (2001). For each domain, participants were asked to choose a value from 0 = not willing to take a risk at all to 10 = very willing to take a risk. Furthermore, we test the relationship between high risk aversion and pest prevention effort (see the robustness check section for details).

According to Result 3.1, as we consider state-dependent risks, prevention effort increases with greater uncertainty in the cost of pest control and loss due to infestation in period 2. In our case study, this links to the marketing and processing strategies farmers adopt. However, the relevant variable, self-processing and direct marketing, contains information that could potentially have opposite relationships with prevention. On the one hand, farmers who undertake self-processing and direct marketing face lower uncertainty of selling their products in case of infestation, and therefore less effort in prevention. On the other hand, self-processing implies possible investment in additional equipment for processing, therefore higher stakes in the case of infestation, and more effort in prevention. Thus, we do not form an empirical hypothesis on the sign of this variable.

According to Result 3.2, as we consider background risk in the theoretical model, prevention effort increases with higher general uncertainty regarding revenues from crop production. Thus, we expect farmers who take out crop insurance and diversify their income through off-farm work and investment to put less effort in pest prevention. In our context, crop insurance is a peril-specific insurance that covers damage from hail and other elementary damages but does not cover pest related damages (Finger & Lehmann, 2012, Möhring et al., 2020). We note that the purchase of crop insurance can also be associated with risk preference, since insurance purchase is associated with higher risk aversion (Knapp et al., 2021). As we also include risk aversion in the model, we consider insurance as a proxy of background risk faced by farmers holding risk preference constant.[12]

We summarize the discussion into the following hypotheses:

H1: *Prevention effort is higher for varieties more susceptible to spotted wing drosophila, and when farmer experienced higher pest pressure previously.*

[11]We note that these proxies provide imperfect measures of past pest pressure in a farmer's nearby region. For instance, a relatively high density of prevention measures in the nearby region could reflect both higher pest pressure and spatial spillovers in farmers' prevention actions. In addition, perceived infestation in a previous period may reflect pest pressure and effectiveness of pest control measure. In the empirical analyses below, we include different subsets of the proxies of previous pest pressure in the regression to check for robustness.

[12]Nonetheless, we are aware of the challenge of disentangling the role of risk preference from crop insurance, and interpret our estimated empirical relations as correlation.

TABLE 1 Summary statistics of area planted and prevention measures by most relevant grape variety

Susceptibility level	Variety	Number of vineyards	% Out of total area	Used prevention (% within variety)
Low	Sauvignon Blanc	12	1.3%	41.7%
Low	Chardonnay	21	3.6%	57.1%
Low	Chasselas	35	28.7%	48.6%
Med-High	Pinot Gris	14	2%	71.4%
Med-High	Riesling	22	2.7%	63.6%
Med-High	Gamaret	26	5.2%	73.1%
Med-High	Merlot	36	13.6%	58.3%
High	Gamay	21	10.4%	57.1%
High	Pinot Noir	62	32.6%	66.1%

Note: The nine most grown varieties according to the 2018 survey are presented. Each vineyard consists of one single variety.

H2: *Prevention efforts is lower for farmers with higher risk aversion in the domains of market and price, production, and external financing.*

H3: *Prevention efforts is lower for farmers with crop insurance coverage.*

4 | ECONOMETRIC FRAMEWORK

In this section we present the econometric framework for testing the relationship between farmers' prevention action and the relevant factors discussed in the theoretical analyses.

We test the hypotheses in the following linear probability model:

$$Prevention_i = X_i\beta + u_i.$$

We define the dependent variable, $Prevention_i$, to be a binary variable that equals 1 if farmer i takes one of the prevention measures: sanitation measures, early harvest, or installing insect nets, and 0 otherwise. X_i contains a vector of independent variables (discussed in detail below). u_i is an error term.

Table 2 presents independent variables that are potentially associated with prevention action based on our theoretical analyses, variable description, and summary statistics.

Furthermore, we control for farm and farmer characteristics including farmer's age, gender, succession of the farm, percentage of earning from viticulture, and the size of the vineyard. We also include a dummy variable for the year of the survey from which the proxies for previous pest pressure is extracted (i.e., 2017), controlling for common shocks that affected overall pest pressure, and canton (member states of the Swiss Confederation) dummy variables that address potential impacts from canton-level extension services on pest control decisions (Wuepper et al., 2021). While several variables have relatively high pairwise correlations (e.g., the correlation between each pair of risk preferences in market and prices, production, and external financing is above 0.5, see also Supporting Information: Figure A1 for a correlation plot), when included in the model, the variance inflation factor is below 3 for all covariates. We therefore let the risk preference in different domains enter the model both jointly and separately.

In several alternative specifications, we check whether the estimates from the main specification are robust to the covariates and the sample construction. We discuss the details of the robustness checks in Supporting Information: Appendix A5.

TABLE 2 Variable description and summary statistics

Variable	Description	Type	Mean	SD
Average perceived infest	Neighborhood[a] average of perceived infestation in previous period for the respective variety	Continuous	0.42	0.40
Average past labor measure	Neighborhood[a] average of pest management strategy applied in previous period: Labor-intensive preventative measures	Continuous	0.59	0.23
Average past investment measure	Neighborhood[a] average of pest management strategy applied in previous period: Investment-involving preventative measures	Continuous	0.03	0.07
Average past insecticide	Neighborhood[a] average of pest management strategy applied in previous period: Insecticide	Continuous	0.10	0.15
Susceptibility	Susceptibility of grape variety to spotted wing drosophila	Categorical	See Table 1	
Risk willingness market	Willingness to take risk in market and prices domain 0 = not willing to take a risk at all 10 = very willing to take a risk	Scale (0–10)	4.69	2.81
Risk willingness production	Willingness to take risk in production domain	Scale (0–10)	4.67	2.97
Risk willingness finance	Willingness to take risk in external financing domain	Scale (0–10)	3.12	2.49
Crop insurance[b]	= 1 if respondent purchased crop insurance	Binary	0.57	0.50
Investment off farm	= 1 if respondent had off-farm investment	Binary	0.11	0.31
Work off farm	= 1 if respondent worked off-farm	Binary	0.16	0.37
Create finance reserve	= 1 if respondent created financial reserves (saving for bad times)	Binary	0.39	0.49
Earning from viticulture	Percent of earnings from viticulture: 0 = 0%–25%, 1 = 26%–50%, 2 = 51%–75%, 3 = 76%–100%	Scale (0–3)	1.97	1.18
Processing direct marketing	Farmer undertook on-farm processing and direct marketing of wine	Binary	0.67	0.47
Previous exp yield loss	Additional cost (in percent) expected in the previous period for measures to be taken against spotted-wing drosophila: 0 = 0%, 1 = 1%–25%, 2 = ≥25%	Scale (0–2)	0.74	0.43
Previous exp additional cost	Expected yield loss caused by spotted-wing drosophila in the previous period: 0 = 0%, 1 = 1%–25%, 2 = ≥25%	Scale (0–2)	0.88	0.46
Male	=1 if survey respondent is male	Binary	0.96	0.19
Successor	=1 if farm has a successor	Binary	0.31	0.46

(Continues)

TABLE 2 (Continued)

Variable	Description	Type	Mean	SD
Age	Age of survey respondent	Continuous	51.1	10.6
Area	Area of vineyard (acre)	Continuous	165.6	324.1

[a]Neighborhood is defined as vineyards of the same grape variety within a 10 km radius of each farmer's postal code location. Within each neighborhood, we calculate the average of previous perceived infestation, prevention measure, and insecticide application for the respective variety.

[b]Crop insurance comprises protection against hail and other elementary damages (see Finger & Lehmann, 2012).

5 | RESULTS

Table 3 presents coefficient estimates of factors relevant to farmers' adoption of general prevention actions. Column (1) corresponds to a model with all domains of risk preference jointly in the model, and in columns (2)–(4) risk preference in different domains enter the model separately. We find that consistent with hypothesis 1, prevention increases with higher perceived pest pressure in previous periods by neighboring growers of the same variety. Specifically, prevention is associated with a higher average level of adoption of labor-intensive measures in a previous period in the farmer's neighborhood. For a farmer with all neighboring farmers (100%) adopted labor-intensive measures in a previous period (which suggests very high pest pressure in the neighborhood), the likelihood that the farmer adopts prevention measures is almost 50 percentage points higher compared to a farmer with no farmer (0%) in the neighborhood who adopted prevention measures. This reflects that higher past pest pressure may have necessitated the use of prevention measures in the past, and labor-intensive measures are the predominant choice by farmers.

In terms of risk preference, as we include risk preferences in all three domains in the model, none bears statistical significance, which is possibly due to the correlation among the three domains. Entering the model separately, farmers more willing to take risks in production and external financing are more likely to adopt prevention measures. Farmers that are most willing to take risks in the domain of production and external financing are, respectively, 24 and 29 percentage points more likely to adopt prevention measures compared with those not willing to take risks at all (columns (3) and (4) in Table 3, respectively). This is in line with hypothesis 2, which draws on Result 2 from our theoretical analysis, that for the class of the power utility function which reflects risk prudence, higher risk aversion (lower willingness to take risk) is associated with higher marginal cost of pest prevention in the first period, and lower marginal benefit in the second period. Furthermore, these results are consistent with arguments in Finnoff et al. (2007), that more risk averse farmers are less likely to take prevention measures due to the less certain net return from this action.

In line with hypothesis 3, farmers with lower background risk (proxied by the uptake of crop insurance) are less likely to adopt prevention measures by 19 to 23 percentage points compared with farmers without crop insurance. As such, farmers' decisions on risk management strategies on different risks are interconnected (e.g., crop insurance vs. pest prevention). Farmers who adopted on-farm processing and direct marketing are around 15 percentage points more likely to adopt prevention measures, which possibly reflect the higher stakes involved due to investment in processing equipment. Farmers who expected higher additional cost due to spotted wing drosophila in a previous period are more likely to adopt prevention measures, with an increase of additional cost by 25 percentage points (interval of increment of the variable) associated with higher probability of using prevention measures by 33–35 percentage points. These results likely reflect that farmers planned to continue with the measure they previously adopted. Male farmers, which consist the vast majority of the sample, are much more likely to adopt pest prevention measures than female farmers. Farms with successors established, and farms of larger sizes are relatively more likely to adopt prevention measures.

TABLE 3 Coefficient estimates of independent variables on pest prevention adoption

	(1)	(2)	(3)	(4)
Average past perceived infest	−0.091	−0.030	−0.067	−0.068
	(0.109)	(0.107)	(0.108)	(0.107)
Average past labor measure	0.498***	0.495***	0.474***	0.495***
	(0.153)	(0.154)	(0.152)	(0.151)
Average past invest measure	0.353	0.297	0.267	0.369
	(0.449)	(0.450)	(0.446)	(0.446)
Average past insecticide	0.302	0.291	0.311	0.319
	(0.258)	(0.260)	(0.257)	(0.257)
SusceptibilityHigh	0.062	0.024	0.052	0.048
	(0.102)	(0.102)	(0.102)	(0.102)
SusceptibilityMed-High	0.043	0.039	0.052	0.036
	(0.076)	(0.076)	(0.075)	(0.075)
Risk willingness market	−0.019	0.009		
	(0.017)	(0.013)		
Risk willingness production	0.020		0.024**	
	(0.016)		(0.012)	
Risk willingness finance	0.026			0.029**
	(0.017)			(0.013)
Crop insurance	−0.192**	−0.226***	−0.203**	−0.202**
	(0.080)	(0.080)	(0.080)	(0.079)
Ag diversification	−0.087	−0.133**	−0.106	−0.107
	(0.080)	(0.079)	(0.080)	(0.079)
Investment oĐ farm	0.001	0.046	0.026	0.011
	(0.124)	(0.124)	(0.123)	(0.123)
Work oĐ farm	0.087	0.067	0.057	0.093
	(0.091)	(0.089)	(0.089)	(0.089)
Create finance reserve	0.107	0.083	0.109	0.090
	(0.082)	(0.082)	(0.082)	(0.081)
Earning from viticulture	0.015	0.009	0.012	0.006
	(0.032)	(0.032)	(0.031)	(0.031)
Processing direct marketing	0.152**	0.155**	0.152**	0.142*
	(0.072)	(0.073)	(0.072)	(0.072)
Previous exp yield loss	−0.050	−0.073	−0.049	−0.093
	(0.089)	(0.086)	(0.082)	(0.084)

(Continues)

TABLE 3 (Continued)

	(1)	(2)	(3)	(4)
Previous exp additional cost	0.349***	0.327***	0.329***	0.346***
	(0.080)	(0.080)	(0.079)	(0.079)
Male	0.404**	0.455***	0.442***	0.418**
	(0.162)	(0.162)	(0.161)	(0.161)
Successor	−0.134*	−0.109	−0.128	0.138*
	(0.078)	(0.078)	(0.077)	(0.078)
Age	0.002	0.001	0.002	0.001
	(0.003)	(0.003)	(0.003)	(0.003)
Area	0.0002*	0.0002*	0.0002*	0.0002*
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Observations	249	249	249	249
Adjusted R^2	0.261	0.244	0.258	0.261
F Statistic	3.496***	3.430***	3.608***	3.648***

Note: Dependent variable = 1 if farmer adopted pest prevention strategies. Model in column (1) includes farmer risk preference in all three domains; in columns (2)–(4), risk preference in each domain enters the model separately. All models include year and canton dummy variables. Standard errors are in parentheses.

*, **, *** denote statistical significance at the 10%, 5%, and the 1% levels, respectively.

6 | CONCLUSION

Pest prevention can play an important role in reducing potential pest pressure and thus reducing pesticide use. Pest prevention thus contributes to reach ambitious pesticide policy goals to reduce pesticide use while maintaining quantity and quality of production. Yet the adoption of pest prevention measures remains often low and below the social optimum. We provided a theoretical and empirical perspective on the economics of pest prevention. We developed hypotheses and tested them using an empirical application for Swiss grapevine producers' decisions to use preventive measures in response to the invasive pest *D. suzukii*. We find that prevention efforts increases with perceived pest pressure based on prior experience, and decreases with the cost of prevention relative to farmers' wealth. Furthermore, we show that higher risk aversion hinders farmers' prevention efforts. Finally, we find that reduced background risk, for example, by using crop insurance, decreases farmers' level of pest prevention.

Our results are of high policy relevance. We provide insights why pest prevention is not necessarily attractive for farmers, even if it seems so from a cost–benefit perspective. This results in preventive efforts below the social optimum, resulting in an overuse of pesticides. The uptake of preventive efforts shall be strengthened by targeted policies. This may involve push and pull strategies, that is, subsidies and taxation of insecticides (see e.g., Finger et al., 2017). A key feature is to also reduce the risks arising from prevention. Targeted information and extension service may provide also an opportunity to reduce perceived risks of pest prevention by farmers and thus facilitate the uptake of preventive efforts (Wuepper et al., 2021). Since measures such as insect nets may be particularly effective in protecting crops in areas highly susceptible to *D. suzukii*, targeted support to farmers on prevention measures in regions of high pest pressure could enhance the effectiveness of pest control not only to individual farmers, but also help contain the spread of the pest in the region. Such support may be particularly relevant to farmers facing financial constraints in investing in pest prevention device, or are less willing to take financial risks in this regard. Furthermore, we show in farmers' choices of risk management strategies are interconnected. In particular, crop insurance can be associated with lower use of pest prevention. Policy makers thus shall account for these possible spillover effects of crop insurance, and consider joint subsidization of different risk management strategies, tailored toward sustainable agricultural practices (e.g., Möhring et al., 2020). Finally, in light of the spatial connectedness of pest pressure and effectiveness of pest prevention measures, future research on the neighborhood effects of adoption of pest prevention measures would contribute to cost-efficiency of private and public investment in pest management.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the ETH Zürich Research Collection at https://doi.org/10.3929/ethz-b-000588689.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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