Rev Agric Food Environ Stud
https://doi.org/10.1007/s41130-024-00217-w

RESEARCH ARTICLE

Multiple agricultural risks and insurance—issues, perspectives, and illustration for wine-growing

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Received: 18 September 2023 / Accepted: 2 July 2024

Abstract
Agricultural producers face multiple risks, including climatic, disease, and market risks, that make crop insurance especially valuable to them. However, risk interactions raise specific issues: The value of prevention efforts in a multiple risk context, risk correlation, and compounded effects (whereby the realization of a risk makes it difficult to prevent another one) all affect the design and effectiveness of insurance. In contrast to the US, the EU-subsidized crop insurance creates different financial conditions for climate and pest risks and increases expertise costs. We discuss how this affects input use and disproportionately disadvantages organic producers because of compounded effects. We report on an experiment bundling a real pest insurance contract with an agronomic protocol aiming at reducing treatments, for vine-growing in the South-West of France. The experiment highlighted the costs to separating risks in insurance contracts, as well as the need for insurance to help transition to greener practices.

Keywords Multiple risks · Insurance · Wine-growing · Pesticides

JEL Classification D80 · Q12 · Q14 · Q18

Introduction

Agricultural production is a textbook illustration of compounded and multiple risks: Farmers face climatic risks of several types (excess rainfall, floods, drought, frost, hail, extreme heat, tornadoes, and storms...) as well as fires, pest attacks from various

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parasites (aphids, grasshoppers, beetles...), and crop diseases (e.g., downy and powdery mildews, black rot for vines) on top of financial risks due to local or world price fluctuations. The large fluctuation in the price and availability of wheat and mustard in 2022 is but one among many examples of global risks. Agricultural workers and close residents also face health risks related to the application of chemical treatments. Despite its prevalence in the lives of farmers, the multiplicity of risks has received limited attention in the academic literature.[1]

These multiple risks differ in their nature, including from the point of view of economic analysis. Some are nearly impossible to avoid and even predict (e.g., tornadoes). Others can be partly prevented thanks to adequate but costly equipment, for some crops but not all (e.g., nets to prevent degradation from hail, heaters to protect fruit trees from frost...). Some can be partly prevented or their consequences can be lessened thanks to intensive labor and pest-control management techniques (e.g., crop rotation, intercropping, adequate variety selection). Disease risks can be controlled to some extent thanks to chemical inputs (e.g., fungicides). Financial risks can be managed thanks to financial diversification strategies—for large farms—and stock management (e.g., in wine, building "climatic reserves" for future years). A major tool to address farming risks is crop insurance, which coexists with self-insurance and prevention efforts.[2] Crop insurance is very largely subsidized throughout the world (Australia being an exception). However, the adequacy of existing insurance contracts is questioned in the context of multiple risks that interplay, some of which are exogenous and others endogenous to farmers' behavior.

We argue that correlations and interactions between risks may not create specific problems by themselves, but restrictive regulations to benefit from public subsidies, because they do not account for these interactions, may lead to inadequate incentives and additional challenges for insurers. The European subsidized crop insurance indeed isolates risks, so that insurance against pests and diseases cannot be bought at the same highly subsidized rate as insurance against specific climatic risks. We analyze some consequences this has on the incentives to adopt greener practices (fewer pesticides). We also report on specific challenges it raises for insurers willing to offer green insurance products.

The case of vine-growing in France illustrates these points. Vine-growing is an interesting case to study as its end product, wine, is very valuable, whereas prevention chemical treatments are cheap, yield volatility is very large, and grapes are very sensitive to both climatic and cultural conditions. We report on an experiment run

[1] Based on the analysis of 3283 studies, Komarek et al. (2020) find that 66% focus only on production risks ("agricultural risk"). Only 15% of studies consider more than a single risk, out of the different risks that they separate. They distinguish between five different risks: agricultural, market (prices), institutional (regulations, policies...), personal (health, divorce...), and financial. In this article, we will focus on the risks that are directly linked to agricultural production. These risks are sufficiently diverse that their interactions need to be taken into account.

[2] As is customary in the literature, we use the term "self-insurance" to refer to actions that reduce the *size* of a loss (other than through financial market insurance) and the terms "prevention" or "self-protection" to refer to actions that reduce the *probability* of a loss. We will also use the expression "scope of insurance" to refer to the type of risks that are being covered by an insurance policy.

in the context of the VitiREV project,[3] (Raynal et al., 2022), where we provided a real insurance contract, managed by a large French insurer, to two cooperatives who agreed to treat vines according to a specific protocol based on a prediction Decision Support System (DSS). This "eco-agronomic" experiment has run for 4 years and has highlighted both the ability to use correlation of risks to better adjust treatments and the need to adjust the insurance framework to adequately meet the constraints of both growers and insurers. In particular, distinguishing between losses arising from climate and from disease turned out to be too costly or even impossible. It strongly restricted the willingness of insurers to provide a green insurance contract. Growers could also use this distinction strategically. This militates for insurance contracts that cover multiple risks rather than specific subsets of all the risks faced by growers.

Different forms of interactions between risks

We exclusively focus in this article on challenges to insurance that stem from the multiplicity of risks. Other challenges exist. In particular, agricultural risks tend to be correlated across policyholders. This is due both to common climatic shocks and to disease propagation. Insurers therefore need access to a sufficiently large customer area and to financial diversification options. The multiplicity of risks creates additional difficulties for insurers and takes different shapes.

1. *Interdependent protection values:* Even in the absence of any direct link between two risks, the value of being protected against a crop risk (A) often depends on the degree of protection that one has against other risks (B, C,...). The occurrence of a climatic adverse event changes a farmer's incentives to exert effort and spend on labor and chemical inputs. This is true for decisions that are taken after the realization of an adverse event, but also for decisions that are taken before, since the grower anticipates the possibility of this event.
2. *Correlated risks:* Some diseases such as powdery mildew are correlated to heat and drought, increasing crop losses in situations where plants may be more sensitive. Downy mildew occurrences are correlated to rainfall. As in the case of vine-growing that we detail later, the occurrence of an event related to a given risk (e.g., rain) may be a predictor of a higher likelihood of another risk (e.g., downy mildew).
3. *Joint realizations and distributions:* In link with the previous point, historical data provides information on joint distributions but is rarely informative on a single risk taken in isolation from its context. Data indeed bears on losses for various years, but each year is characterized by a combination of occurrences of risks A, B, C,... that can be so complex as to prevent the identification of the effect of, say, risk A. Under changing conditions (for instance due to climate change), that affects the frequency of realizations for various climatic risks, and the actual distribution of a given risk may be quite different from the one estimated based on historical

[3] VitiREV, which will be mentioned several times in this article, is a public-private consortium co-funded in 2019 by the French government and led by *Conseil Régional de Nouvelle-Aquitaine* with an action plan to accelerate innovation for the reduction of pesticides in its vineyards.

realizations. Another challenge associated to the joint realization of different risks is that it may be quite difficult to allocate agricultural losses to a given cause.

4. *Compounded effects:* The occurrence of an adverse state of nature concerning a given risk, say A, may prevent the farmer from being able to use prevention measures against other risks, say B. For lack of a better term, we refer to this situation, which links the severity of a risk to the realization of another one, as "compounded risks." An example is provided by excessive rain, which washes out some treatments against pests and prevents sprayers and other heavy machines from entering the fields.

The fact that the value of a protective or preventive measure depends on other risks (1) primarily affects insurance claims because of moral hazard effects. The correlation of risks (2) affects the variance of indemnities for insurers who offer protection against multiple hazards. The conditionality of distributions of a risk upon another one (3) raises the possibility of using current realizations of a risk as predictors of other risks. But the fact that different negative risks can be realized in the same growing season makes it very difficult to assess which proportion of losses should be attributed to which risk realization. An insurance contract in which the conditions and levels of indemnification depend on the cause of losses therefore entails expertise costs. Last, the compounded risks (4) imply that an insurance contract that protects only against narrowly defined risks may ignore the impossibility to self-protect against other risks, which creates distortions in the attractiveness of various protection measures, in particular greener ones. This is a major theme of this article. It is a less visible cost of separating risks in insurance.

These different aspects will have more or less bite on insurance depending on the applicable regulatory framework. We detail below the two polar cases of the US and the EU-subsidized systems, as we will use them in the remainder of the article to contrast the impact of risk multiplicity when all risks are covered in the same way by insurance and when they are separated by the regulatory framework.

Insurance scope under multiple risks: US versus Europe

Insuring all risks: the US revenue insurance

The US crop insurance, which is highly subsidized, is by far the largest agricultural policy instrument (Glauber, 2013). Public support to crop insurance represents more than twice the premium paid by farmers (Mahul & Stutley, 2010). It can be based on either revenues or yield. Yield insurance covers losses stemming from climatic hazards like hail, drought, fire, excessive moisture, as well as damage from pests and diseases. Revenue insurance is now the most popular. It encompasses any reduction in generated revenue, whether resulting from production loss, shifts in market prices for crops, or a combination of both.

Insuring only climate-related risks: the EU crop insurance

To the contrary, the EU-subsidized insurance program does not directly protect against yield losses due to pests and diseases. Although it protects against multiple risks, the risks covered are limited to various climatic risks and their direct consequences. Crop insurance policies protecting against single or multiple risks are available in all Member States, predominantly with a basic hail coverage (Chartier et al., 2017). Implementation varies across States. The Multi-Peril Crop Insurance (MPCI), which encompasses yield insurance and combined-peril insurance, is available in the majority of Member States with a few exceptions where the insurance market only offers standard hail coverage (Belgium and Denmark). Most MPCI insurances exclude or only partially include protections against drought, storm, and excessive rain.

The "risk management toolbox" of the Common Agricultural Policy (CAP) allows for the use and public support for insurance and is capped to 70% of premiums or annual payments into mutual funds (Chartier et al., 2017). Adoption rates greatly vary across Member States.[4] Some historical tendencies explain some of the variations in implementation and adoption rates (Meuwissen et al., 2018). Other factors stem from the different climatic and geological contexts and the different crop specializations across Europe. In France, the CAP-subsidized system was reformed in 2023, with a particular focus on providing incentives to farmers to buy insurance (cf. Appendix A and Rozan and Spaeter, 2024). Farmers may indeed be reluctant to buy insurance if they believe that the state will issue exceptional compensation in the case of exceptionally severe shocks, as happened in the past.

The remainder of this article is organized as follows: Section Interdependent values of protection shows how insurance can modify farmers' incentives to exert prevention and precaution efforts, due to the interdependence of protection values. In Section Correlated risks and joint realizations, we describe how risk correlation and joint realization of adverse events affect insurers. Section Compounded effects and insurance discusses how compounded effects distort the attractiveness of different cultivation practices. We illustrate in Section The effects of multiple risks in French vine-growing the interactions between multiple risks, regulatory constraints on insurance, and pesticide use for vine-growing in France. Section Discussion and conclusion concludes and offers some perspectives in an evolving context.

Interdependent values of protection

In a multiple-risk context, the value of prevention efforts against one risk depends on the impact of other risks (interdependent values). A consequence is that the value of being protected against some risk depends on whether one benefits from an insurance policy, even if it does not cover that same risk. Being insured changes the attractiveness of investing in prevention and protection efforts, which has consequences on the distribution of losses. This is a problem for insurers in situations where prevention and protection efforts are not verifiable (i.e., cannot be proved to third parties). Insurers then face "moral hazard" on the part of farmers.

[4] In Germany, uptake of hail insurance is the most common practice, while in Hungary, Italy, and Spain, MPCI is the dominant type of coverage. Bulgaria, Cyprus, Greece, Hungary, and Poland have made crop insurance compulsory. Other states have a tradition of less interventionism in agriculture (such as Germany).

The moral hazard problem in insurance has long been recognized. In a classical analysis with a single risk, Ehrlich and Becker (1972) highlighted how financial market insurance could crowd out self-insurance efforts. An important result of their article is however that market insurance can be a complement to self-protection (or prevention) efforts. Therefore, moral hazard associated with financial market insurance is not an inevitable problem, at least under complementarity. The multiple-risk context increases the scope for moral hazard due to substitutability: For instance, investing in nets is of lower value if fruit production is likely to also suffer from drought or rain.

Efforts verifiability

Some risks are partly endogenous to farmers' choices, and these choices are not all observable or verifiable. Verifiability is a stronger requirement than observability, since it imposes that evidence can be shown in court. It determines which conditions can be effectively written in a contract. Some efforts made to prevent damage from climatic causes, such as investing in hail nets to protect fruit trees, heaters against frost, or irrigation systems, are associated with observable expenses. Efforts to avoid pests and diseases can be linked not only to the quantity of pesticides used but also to the timing of treatments; both of which are usually required by law to be registered, but checking the registers is costly. The quality of the monitoring of fungic pressure, efforts to use intercropping and crop rotations to lessen pest attacks, or labor-intensive actions to help improve soil quality and plant vigors are much more difficult to observe and more susceptible to moral hazard. The care with which the farmer monitors plant health, her expert and timely use of pest management techniques, diligence in harvesting in stormy conditions and in organizing treatment applications at the adequate moment all tend not to be easily verifiable.

Insurance scope and moral hazard under multiple risks

The empirical link between crop insurance and moral hazard has been widely studied since seminal articles on input use in the US (Horowitz & Lichtenberg, 1993; Quiggin et al., 1994; Smith & Goodwin, 1996a). Under the US multi-peril yield or revenue crop insurance, farmers are insured against a variety of risks, say A, B, C, and D, and can privately choose their pesticide use, which protects against disease risk D. Because insured farmers receive indemnities independently from the source of losses, they have *a priori* less incentive to mitigate potential damages due to pests and diseases than their uninsured counterparts. Empirical results in the US are mixed: contrary to the above insight, Horowitz and Lichtenberg (1993) show that holding individual yield insurance (FCIC insurance) is associated with significantly higher expenditures on pesticides (+21%) and significantly more acreage treated with both herbicides and insecticides (+7% and +63%) by US Midwestern corn producers in 1987, but Smith and Goodwin (1996b) find that insurance reduces pesticide use, as expected.

The European crop insurance system can in theory counteract the moral hazard issue associated with prevention efforts, as shown by Goodwin (2001). It covers climatic risks C but not losses due to the disease risk D, so that incentives to prevent diseases should remain high. However, a relationship between insurance uptake and pesticide use still persists empirically: Chakir and Hardelin (2014) identify two reasons why insurance uptake and pesticide use *positively* interact in the EU. First, risk-averse farmers may both tend to use more pesticides, against risk D, and to insure more, against other risks. So risk aversion can create a positive correlation between insurance adoption and pesticide use. Second, pesticides not only reduce risk but also increase expected production, consequently increasing exposure to climate-related risks (C), that can be insured. Producers who anticipate higher yields may tend to acquire more insurance because of their heightened vulnerability to climate-related risks. Using data from French rapeseed producers between 1993 and 2004, Chakir and Hardelin (2014) indeed find a positive relationship between the quantity of pesticides employed by farmers and their demand for hail insurance. Möhring et al. (2020) also study on the impact of climatic crop insurance on pesticide use for French and Swiss farmers. They account for extensive margin effects, i.e., land re-allocation effects (Wu, 1999). For the period from 2009 to 2015, they confirm a positive relationship between insurance and pesticide use in France.

Vine-growing appears to be specific with respect to this relationship. It is a highly intensive culture, which accounts for 15–20% of pesticide use in France for only 3% of cultivated surfaces[5]. The potential impact of insurance on pesticide use is therefore of primary concern in this sector. For French vine-growers from 2002 to 2007, Aubert and Enjolras (2014) find that being insured has no impact on pesticide consumption over the years. However, a dynamic analysis shows that among vine-growers, those who increase their insurance coverage are also those who reduce their consumption of pesticides the most and receive greater compensation (in contrast with Chakir and Hardelin, 2014). Enjolras and Aubert (2020) study French farms cultivating field crops and quality wine between 2008 and 2012. They find no discernible influence on pesticide use on the purchase of crop insurance, even when accounting for changes in land allocation within the farm (in contrast with Möhring et al., 2020).

The empirical studies discussed above therefore highlight the sensitivity of the impact of insurance contracts to both the scope of insurance (as defined by the regulatory set-up for subsidized insurance) and the exact crop considered.

Damage assessment costs

Assessment and incentives Some expert appraisal can be needed to avoid negligent care by insured farmers (a form of moral hazard). In some cases, checking the recording of treatments done (which is mandatory in most developed countries) is enough to ensure that farmers have spent enough to protect their crops. However, other contexts call for a more in-depth assessment of protection efforts. Expertise can be very costly

[5] Based on sales data from the French Crop Protection Association, an initial report in 2005 (Aubertot et al., 2005) indicated that vines accounted for 20% of French pesticide expenditure for 3% of French agricultural land in 2000. Five years later, another report (Butault et al., 2010) put forward the figure of 14.4% of pesticides for 3.3% of French agricultural land in 2006, based on statistical data from the French Ministry of Agriculture. It was also calculated that an average of €394 per hectare of pesticides is spent on vines, a figure exceeded only by fruit production (€590/ha) and horticulture (€527/ha), but on a much smaller share of French agricultural land for each of these two crops (around 1%) (Butault et al., 2010)

because of the multiplicity of damage sources and the difficulty in assessing responsibility. In the special case of wine, experts agree that it is often nearly impossible to assess whether a low yield at the time of harvest is due to bad climatic conditions or to inadequate treatments (Aubert et al., 2020; Raynal et al., 2021, 2022). Being unable to assess the source of losses does not necessarily prevent insurers from providing adequate effort incentives to farmers, but it makes them more costly. To provide such incentives, the indemnity must indeed be related as closely as possible to farmers' efforts (Holmström, 1979). If output is affected by other elements than effort, the costs of asymmetric information (including information rents) increase.

Suppose losses are covered independently of their cause. In that case, the cost of moral hazard is mostly that insurers will shift the contract away from the full-information one (in particular in terms of risk-sharing, with higher deductibles, and also information rents to farmers protected by limited liability). These contracts will be less profitable and less efficient, the lower the correlation between effort and yield. But if contracts do not cover losses attributed to some risks (such as disease risks or risks due to neighbors' behavior), expert assessment becomes necessary. This assessment is an audit which is costly in itself, but reduces information costs (information rents and inadequate risk-sharing). Note that if insurers do not choose to spend on expertise when this is not made necessary by regulations, it implies that it is more costly than the information costs that expertise reduce.

It should be noted that with the development of precision agriculture, more and more data becomes available and the traceability of farmers' actions should notably improve in the future—at least for bigger farms that will have the financial resources and incentives to invest in digitization and precision tools. The insurance contract must be very precise as to the conditions under which the farmer is considered to have taken adequate actions, and it is likely that some expertise costs will remain necessary to assess the validity of some claims, especially in smaller farms and in the shorter run.

Correlated risks and joint realizations

Some climatic risks tend to be correlated, such as high temperature and drought or hail and out-of-season frost. Climatic risks can also be correlated with some fungi development, as is the case for humidity and downy mildew. Correlation impacts input use by insured farmers, as well as the variability of insurers' portfolio of claims.

Correlation and input use under insurance

As mentioned, in the EU-subsidized insurance system, one risk (climate) is insurable, while another one (as downy mildew), correlated with the former, is not. This second risk corresponds to a "background risk." This situation is theoretically studied in Mahul (2001): He shows that this correlation can drastically change the optimal terms of insurance compared with a setting where risks are independent (studied in Mahul, 1999). He also shows that the purchase of actuarially fair weather insurance (i.e., such that the insurer makes no profit) induces a risk-averse and prudent farmer to decrease their level of risk-decreasing inputs such as pesticides. Interestingly, this theoretical result may explain why climate insurance seems to increase input use in the EU for several crops, but not so much for vine-growing (cf. Section Interdependent values of protection), where insured and non-insured risks are more strongly correlated, which creates a countervailing force.

Correlation and the variability of insurers' profits

The scope of insurance affects the variability in payments both at the private and public levels. Since US yield insurance covers all types of agricultural risks to output, risk correlation is diffused compared with the EU system which covers a more narrowly defined set of risks. The same does not necessarily apply for the US revenue insurance, as revenues are computed on the basis of general prices that apply to all producers of given crops. Prices for different crops may not be much correlated, but an insurance company specializing, for instance, on revenue insurance to wheat producers will still face a correlated portfolio of claims.

To summarize, one can expect the correlation problem to be weakest for all-cause yield insurance (provided that the insurer base is sufficiently heterogeneous in terms of location and/or crop), stringer for US revenue insurance because of price correlation (especially if a crop, such as wheat or maize, is dominant among clients), and possibly strongest for an insurer in an EU Member State that pays out indemnities mostly because of frost or drought, with clients that tend to be concentrated in relatively small regions (compared to large countries such as the US, Brazil, or China). Reinsurance is therefore of primary importance for European insurers.

The impact of climate change

Global climate change entails uncertainties on the frequency and extent of various climatic risks, so insurers may not fully rely on past data to assess the financial viability of contracts. Because of the impact of climatic factors such as heat and humidity, climate change is predicted to change not only the frequency of natural hazards but also that of crop diseases. The change can be positive or negative depending on the regions, as reviewed in Juroszek and von Tiedemann (2015) (with impacts that tend to be positive for Brazil for instance). Using an infection model driven by air temperature and leaf wetness data, Bregaglio et al. (2013) estimate, for 2030 and 2050, an overall increase in the number of infection events in Europe. The expected increase ranges between 20 and 100% for brown rust on wheat, so compounded effects are expected to be large for this widespread cereal in Europe. Pequeno et al. (2024) find that climate change, because of rising temperatures and humidity in parts of the globe, will likely increase the occurrence of wheat blast infection, especially in the Southern Hemisphere. This could lead to a reduction of global wheat production by 69 million tons per year, the equivalent of a 13% decrease, by 2050.

This is important for insurers. While they expect an increase in the cost of claims because of an increased frequency of adverse climatic events, they may also be affected by changes in the frequency of diseases if they insure them. The US and EU systems will fare differently, with the US system potentially more directly affected by this indirect effect of climate since it covers disease and pest risks.

Potential joint realizations and assessment costs

Data The difficulty in gathering data and identifying the underlying distributions from the observation of a joint distribution plagues agronomic research. It is heightened by climate change. Despite its large importance, we do not discuss it further as it is mostly, from the point of view of insurance, an applied problem in the search of adequate premiums and profitable markets.

Expertise costs The possibility that losses stem from several concomitant adverse events has direct consequences on expertise costs. In the EU, the subsidized crop insurance rules impose that insurers identify the source of the damage. This increases a cost for insurers, and uncertainty for farmers, compared with a yield insurance similar to the US one. This issue arises for any insurance contract that covers only one type of risk, say risk C (climatic), when another type, risk D (disease), can also induce losses. Then, an expert assessment is needed to ascertain whether an indemnity is due. If farmers can hold several contracts (such as a CAP-subsidized contract for climatic risks and a non-subsidized contract for pests and diseases), they have incentives to assign losses to the risk associated with the most favorable contractual conditions. In a number of cases, even experts may not be able to assess which proportion of losses is due to which source.

Index insurance A typical solution to reduce insurance expertise costs is to rely on index-based insurance (or more precisely, index derivatives, as the use of an index does not qualify for the accounting definition of insurance, Clarke, 2016). Climatic risks can relatively easily be covered thanks to such index-based insurance, given that suitable indices can be built using satellite and meteorological data. This has proven extremely useful for small farmers in developing countries, where expert visits would have represented a prohibitive cost (Ahmed et al., 2020). Index-based insurance can help reduce moral hazard, adverse selection, and administrative costs, despite new problems related to the imperfect overlap between losses to specific farmers and their indemnification (Jørgensen et al., 2020). A main limitation of index-based contracts is the existence of a "basis risk," that is, the risk that the farmer suffers damages but the index takes a value that does not trigger an indemnity (Glauber, 2004; Jensen et al., 2016). The design of the index is therefore of prime importance, as it should be such as to minimize the basis risk (that is, to maximize the correlation between the occurrence of losses and the triggering of an indemnity). Index-based insurance is more difficult to set up in regions in which weather and geographic conditions are very heterogeneous, making it less applicable to the EU than to the US (Diaz-Caneja et al., 2009).[6] It may also be less applicable to vine-growing, where yields are especially hard to predict,

[6] An EU report (Diaz-Caneja et al., 2009) stated that index-based insurance was likely unfeasible in Europe due to the great heterogeneity of weather and geographic conditions (in contrast to the US). Technologies,

than to cereal crops. In the context of global climate change, the index composition should be regularly updated to maintain its relationship with actual losses. Last, an important limitation is that suitable indices are much easier to construct for losses due to climate than for losses due to pests or diseases, despite their correlation with weather correlation.

Compounded effects and insurance

The problem of compounded effects has received limited attention in the literature but has proved to be quite relevant in practice, particularly for organic cultivation. Compounding effects lead to losses much above the losses that each adverse event could have caused. Shah et al. (2020) define them as either "multiple hazards leading to a more severe impact, or a single hazard impacting multiple crops in overlapping crop rotations, leading to a more severe impact overall." Based on a survey of Pakistanese farmers, they find that yield losses due to adverse hazards are highest in situations of compounding effects. Compounded effects can exist even without multiple risks. For instance, a single climatic hazard can affect both crops in an intercropping or sequential cultivation situation. Other compounded effects arise from the adverse realization of several different risks, possibly due to their correlation. For instance, Shah et al. (2020) report that insect and disease infestation are common under hot and humid weather during the reproductive and grain formation stages. They entail larger losses as it is more difficult to fight both.

Compounded effects of rainfall

Excess rainfall (climatic risk C) by itself is not a source of losses for grapes and grains and is not included, in normal conditions, in the EU-subsidized MCPI insurance. Losses due to rain can however be indemnified if a direct causation is observed, such as rain tearing off grains or excess water making them explode. This climatic risk is thus potentially covered by the MCPI but only in very exceptional circumstances.

However, intense rain washes out contact treatments against pests and diseases. Pesticides can be systemic (in which case the treatment penetrates the plant and moves to all tissues) or contact treatments (in which case they remain on the leaf surface). The treatments that are allowed under organic cultivation are typically contact treatments, so organic producers are more hurt by rain washing than conventional ones who are using systemic products. Sustained periods of rain make it impossible to reapply treatments that have been washed out (it would be useless anyway), nor to apply new treatments, be they contact or systemic, as this would cause too much damage to water-saturated soils, or the fields would simply be impassable.

New treatments may be especially necessary in those periods of heavy rain that prevent treatment. This is because rain is correlated to another risk, D, the develop-

including the precision of satellite imagery, have however progressed fast so that this conclusion may no longer be warranted.

ment of downy mildew. Downy mildew is among the most prevalent crop diseases worldwide. It affects many different crops, from grains to fruits and vegetables. It is of particular concern because its development can be extremely fast, so that small, undetected, attacks on plants can lead to 70% of the plant being affected in a week, with dire consequences on output. Choosing resistant cultivars is difficult because of the variety of mildew races that can develop in the same location from 1 year to the next and, in some countries, because of the requirements of denominations of origin to use well-specified cultivars. Fighting mildew is therefore one of the reasons for sticking to intense conventional pesticide use. This is the case for vine-growing, which, as previously said, accounts for a disproportionate share of pesticide use (15–20%) compared to its share of cultivated area (ca. 3%) in France. This has very heavy consequences for the environment, water quality, and human health.

A climatic risk C can therefore cause much damage by preventing farmers from exerting effort against another risk D. Organic producers are especially hurt by rain given the specificity of the treatments they are allowed to use. While conventional producers may (although not always) have access to products that are effective even in these situations, organic producers are left with no measure to secure their output. In the absence of insurance for disease risks, they cannot protect their revenues. Therefore, a regulation that prevents subsidized insurance from covering losses due to these compounded climate-disease risks is ultimately especially detrimental to organic production.

An illustration in vine-growing

A recent occurrence of this situation took place in the summer of 2023 in France. After a very intense and continuous period of rain, vines have been severely attacked by mildew. Vine-growers were expecting large losses. Because of the rain, it was impossible for many growers to go in the fields and apply curative treatments for mildew. They therefore invoked the MPCI insurance as they considered that their losses were largely due to climate (rain) and not simply to the (non-insured under MPCI contracts) mildew disease. Insurers have collectively refused to hear this argument (cf. article (in French) by A. Abellan in VitiSphere on July 28, 2023).[7] Insurers based their decision on the precise wording of the EU-subsidized MPCI regulation. In 2008, under a similar situation, insurers had agreed to indemnify vine-growers. A regulatory extension of the MPCI conditions could therefore help protect vine-growers when the interaction of several risks leads to large losses.[8] Judicial uncertainty however prevails, as our examples show. The interaction between the climatic and the disease risks remains unaccounted for in the current EU-subsidized system.

[7] https://www.vitisphere.com/actualite-99922-refus-des-assureurs-de-couvrir-les-pertes-du-mildiou-un-grand-bras-dhonneur-a-tout-le-vignoble-.html.

[8] The new French regime (presented in Appendix) specifies that the consequences of the ineffectiveness of a treatment or the inability to treat are not covered by subsidized insurance. The 2022 Law however contains some ambiguity with respect to pest- and disease-related risks: it mentions that a future decree would define preventive measures taken by farmers that would allow them to be granted a reduced insurance premium. The official documentation (in French) is https://www.vie-publique.fr/loi/282699-loi-2-mars-2022-reforme-du-regime-de-lassurance-recolte-en-agriculture

The effects of multiple risks in French vine-growing

Wine-growing provides an interesting illustration of a sector exposed to multi-risks. It entails both independent risks (such as hail and most pests) and correlated risks (such as mildew and rainfall or humidity).

We participated in an agronomic and economic experiment in the South-West of France, under the VitiREV project, together with two cooperatives and a large insurer. We describe the experiment in Section The design of the VitiREV experiment. It has the originality of associating agronomic expertise to design an optimized treatment protocol, with a real insurance contract that insures the losses that may arise under the protocol due to pest attacks. The protocol aimed at improving sustainability objectives, under a regional public subsidy of the insurance premium and the extensive use of a Decision Support System. The two main lessons from the experiment (detailed below) are that (i) correlation can be used for the prediction of pest attacks but variability remains quite high, and (ii) the current system of subsidized insurance prevents effectively addressing multiple risks in other insurance contracts.

The design of the VitiREV experiment

From 2019 to 2022 (4 growing years), ca. 100 hectares belonging to two wine cooperatives in southwest France (Bordeaux and Buzet winegrowing regions) tested an experimental protocol for pesticide application, designed to eliminate unnecessary applications, with the safety net of monetary compensation in the event of yield loss attributed to pest attacks.[9]

Ecological objective Whereas winegrowers can only know *a posteriori* whether a particular application was necessary (by observing the impact of its absence, which is of course too costly), Decision Support Systems (DSSs), based on the modeling of the epidemiological phases of the fungi responsible for the main diseases, can now provide them with day-to-day anticipation on the degree of pest pressure, helping to assess when chemical protection is needed. The French Technical Institute for Vine and Wine (*Institut Francais de la Vigne et du Vin* - IFV) developed one such DSS, called DeciTrait®, which is currently marketed to winegrowers. Another DSS developed by the same IFV, OptiDose®, is specifically designed to advise how best to adapt each pesticide dose according to the disease pressure evaluated by models, growing stages of the vine, and the characteristics of the pesticides and sprayers used. By combining these two DSSs in an unprecedented way, and based on a set of complementary rules designed to obtain the best pesticide efficiency (the lowest cumulative doses while maintaining a correct sanitary state of the production), IFV established an experimental Treatment Protocol (TP) indicating daily whether a pesticide should be applied and at what dose. This protocol was the one tested in the VitiREV experiment. It depends on the characteristics of the plot under consideration (e.g., organic or conventional, previous susceptibility to diseases) and requires regular inputs on weather conditions (such as rainfall levels) and any observations of disease symptoms.

[9] Videos, in French, describing the experiment are available at https://umt-seven.hub.inrae.fr/actualites/2024-videos-du-seminaire-arrupvico and, especially, at youtube.com/watch?v=bQS0-Xrh6IA.

The professional participants To encourage professional winegrowers to test the TP in real-life conditions, the authors benefited from the VitiREV program, a broad public-private consortium co-financed by the French government and led by Nouvelle-Aquitaine Regional Council (Nouvelle-Aquitaine including the famous vineyards of Bordeaux, Cognac, Bergerac...), designed to accelerate innovation for the agroecological transition of vineyards. Among the contributors, an insurance company (Groupama) and two wine cooperatives (*Les Vignerons de Buzet* and *Les Vignerons de Tutiac*) agreed to co-construct an original insurance contract that would then constitute the prerequisite for a large-scale experiment of the TP. This contract would cover the risk of losses due to fungus attacks occurring despite compliance with the TP.

The contractual conditions From the insurer's point of view, one main condition for setting up such a contract in the first year was that the considered vineyard should also be insured for climatic risks, under the French MPCI system. This was to ensure that any reduction in yield due to climatic events would not be imputed onto the experimental disease insurance contract. When the cooperative bought an MCPI contract from another insurer, it was decided that experts from both companies would simultaneously conduct their visits and jointly decide on the relative attribution of losses. However, as shown by this experiment, this assessment is extremely difficult to make.

From the point of view of the insured parties, i.e., the cooperatives, the main condition set in the first year was not to have to bear any losses generated by the implementation of the TP. Initially set at 0%, then raised to 5% for the following 3 years, the deductible was set at a very low level from an insurance perspective. The move from 0 to 5% was agreed between the various parties after the first year's observation that it was extremely difficult to measure losses strictly linked to the disease, especially at such low levels, close to the margins of measurement error, and having finally no significant effect on yields.

Thus set up, the contract took the form of an extension of the MPCI contract, dedicated to protection against grape volume losses attributable to a set of three diseases (downy mildew, powdery mildew, and black rot), under cover of the correct implementation of treatments and doses recommended by the TP (a tolerance of 48 h was agreed between the alert generated by the TP and the real application date of the treatment, to take into account human resource constraints).

Despite the insurer's extreme difficulty in pricing an insurance product for a process with no historical basis for its performance, based on IFV's estimate of success, the insurance premium was set at €250/ha. It is important to note that even this low level could not have been borne by the cooperatives alone, as they felt they were already carrying the risk of not honoring their contracts with downstream suppliers in the event of volume losses (a cost perceived as not being compensated for by any monetary compensation received). Contracting was thus aided by subsidies from the VitiREV project and the insurer's commitment to reimburse half the premiums if no compensation was forthcoming.

Each of the two cooperatives chose a number of plots of land between 30 and 80 ha, owned by the cooperative itself and not by one of its members, to be covered by this contract. On these plots, technical monitoring by both IFV and the insurer employees was very close during the treatment periods to provide the best possible information and anticipation for these first experimental set-ups. A yield potential was defined at the start of the season, based on the vine's spring development, to serve as a basis for calculating any losses. In the event of an outbreak of disease with potential yield loss, the cooperative had to notify the insurance adjuster for a report (as is usual for weather damage reports with MPCI) and a calculation of the new yield potential. At the end of the year, a final yield was estimated based on a significant survey of bunches on the plot.

This design was reproduced in four successive years from 2019 to 2022 inclusive. While no compensation was paid for the first few years, the fourth year saw a sharp drop in yield, of the order of 80%, on a 20-hectare plot, giving rise this time to substantial compensation.

Environmental performance was assessed by comparing the intensity of pesticide use per hectare (measured by the Treatment Frequency Indicator, TFI) between the insured plots and other plots close to the cooperative, with equivalent characteristics (grape variety, organic or non-organic management methods). Depending on the year, a reduction of between 30 and 70% has been achieved using this tool.

Correlation between insured and non-insured risks: climate and mildew

A striking example of climate-disease interaction is the *Plasmopara* fungi, responsible for downy mildew; their maturation depends on temperature and precipitation. Plasmopara is native to North America and was first detected in Europe in 1878. Since then, it has been considered one of the worst grapevine diseases that occur during favorable weather conditions (Barrios & Reyes, 2004). Cortiñas Rodríguez et al. (2020) analyze two viticulture areas from North-western Spain during three growth seasons (2016, 2017, and 2018). Their statistical analysis showed that rainfall and relative humidity had a statistically significant influence on the spore concentrations in most cases. While the correlation of risks tends to amplify the losses made in bad years, it is used to help predict the development of diseases and can therefore help minimize treatments while maintaining satisfactory yields, as was done in the VitiREV experiment.

Associating climatic information to treatment recommendations

The protocol uses climatic elements (such as rainfall) and mildew contamination detected by the DSS DeciTrait®to set treatment dates and doses. The system computes the subsequent duration of anti-mildew protection, taking into account the products' mode of action and rainfall washout. These treatments, as carried out within the framework of the insurance protocol experiment with an objective of reduction in pesticide applications, deliberately do not cover all the infections detected or possible over the entire sensitive vegetative period (which goes from April 1st to August 31st).[10]

Every year, at the beginning of the season, spring rainfall prepares the maturation of the fungi stored in the soil, more or less rapidly and in variable quantities depend-

[10] In the Decitrait®version marketed to all winegrowers, the tool advises them to treat their vineyards to protect against each contaminating event. The version used in the experiment allows for more risk-taking as it is more ambitious in terms of treatment reductions.

ing on the climatic conditions. But often these rainfalls do not cause any significant contamination requiring vineyard protection. In practice, however, many winegrowers systematically trigger the first treatments following this type of rainfall event, in order to secure their production. According to our observations, they are often unnecessary.

Some lessons from the experiment

Regulatory constraints

Constructing the experiment has been difficult for a number of reasons. In particular, it has proved very difficult to design a relevant multi-risk insurance contract adding supplementary sanitary cover to the MPCI insurance base: MPCI insurance is not conditioned by the application of a specific production protocol, and its terms exclude pests and diseases. It is subject to a 20% exemption in the event of a claim, which vine-growers find difficult to accept for an insurance such as the one we tested, in which they are asked to take additional risks by reducing treatments. The MCPI is also based on the Olympic average, which vine-growers tend to reject. The MPCI is so highly subsidized that independent insurance contracts are largely not attractive.

In the disease insurance contract used in the experiment, strict observance of the "Insurable Treatment Protocol" specifications is required to minimize the random effect of climatic risk. It is therefore subject to a deductible that has been lowered to 5%, calculated on the basis of the maximum potential yield achieved over the previous 5 years. As said before, a low deductible was necessary for vine-growers to be willing to participate in a contract in which they loose some of their decision-making power and take risks by limiting treatments. This disease insurance contract is therefore not currently being supported nor can it be funded under the current regulatory framework.

Identification of losses A second lesson from the experiment comes from the very large losses observed in 2022. While the insured protocol was quite efficient in the previous years (and also in 2022 on most plots), losses that year have reached 80% of the potential yield on some plots. A first lesson is that despite the DSS, a residual risk remains which requires insurance to protect vine-growers willing to attempt to reduce treatments. This situation also showed the difficulty of (i) assessing yield potential as early as possible in the season and (ii) monitoring the deterioration of this maximum potential, distinguishing between climatic causes (frost, hail, drought, etc., with a 20% retention) and biotic causes (downy or powdery mildews, or black rot, with a 5% retention), in order to determine the origin of the yield loss measured at harvest. Regular (and very costly) expertise is therefore essential throughout the season, and final expertise is not enough to properly guarantee the loss: an early attack of downy mildew causes inflorescences to dry out and fall, which is no longer visible during the summer. Similarly, if the appraisal is carried out too late, it is not possible to make a clear distinction between climatic desiccation due to sun-scald burns and mummified berries following symptoms of brown rot in a downy mildew attack at the bunch closure stage. In this respect, a yield insurance associated with the insurable protocol would have been much easier to run.

Overall assessment The experiment has been very valuable as proof that the correlation between risks can actually be used in order to better predict epidemic dynamics and to avoid unnecessary treatments, thereby achieving higher environmental quality. Convincing growers to adopt the DSS, however, can only be done by securing their returns thanks to a specific insurance. As discussed above, the precise construction of this insurance is complicated by regulatory constraints as well as by implementation constraints to assess the source of losses.

This militates for adjustments in regulation and the inclusion of yield insurance (whatever the cause of loss) in subsidized insurance to favor environmental objectives.

Discussion and conclusion

Main insights

Agricultural producers face multifaceted risks, spanning climatic, disease, pest, technological, and financial uncertainties. This creates both specific challenges that limit the potential of insurance to safeguard farmers' returns and a high need for adequately designed insurance to mitigate losses. The example of vine-growing has shown how the correlation between some weather risks and some pest risks can be harnessed to design better prediction tools and induce more targeted, and fewer, applications of chemical inputs. This however involves a financial risk so that growers are unlikely to engage in such less intensive practices in the absence of a specific insurance for pest-caused losses.

Such insurance is currently not available in most regions and crops in Europe. Regulatory constraints on which insurance contract is eligible for public subsidies have strong consequences on the insurance market and on farmers' behavior, as we discussed. Moreover, while correlation can be used for prediction, the compounding effects between some climatic and some pest risks create specific difficulties that the existing EU-subsidized system cannot address (as exemplified by vine-growing in France in 2023). This militates towards a system where either yield or revenue is insured, independently of the cause of loss (despite the potential moral hazard issues this can reinforce).

Perspectives

Revenue vs. yield insurance Both yield and revenue insurance save on assessment costs as the insurer does not need to identify the exact cause of the losses, contrary to the multi-peril European version. Revenue insurance however presents specific challenges as it requires that revenues be computed. The assessment of revenue may be subjective or too costly to undertake. In the US, revenue is computed based on prices on the Chicago Mercantile Exchange together with farm-level yields.[11] A reason why US revenue insurance is much developed while it is not in the EU can be linked to this mode of computation of revenue: the Chicago market represents a recognized and sufficiently adequate evaluation of future prices that cannot be manipulated by big actors, in a context where prices are sufficiently homogeneous. In contrast, in Europe, crop prices and qualities vary more widely, and no obvious and fully independent reference exists on which to base revenue indemnity. Cereals and fresh produce exhibit very different characteristics and may not be insured following the same rules.[12] Yield insurance appears therefore easier to set up.

Index insurance The use of index-based insurance (or more properly, crop derivatives) is associated with much lower assessment costs but is only available for some crops and risks (mostly climatic), as we discussed. It indeed requires that a solid prediction model linking the index to actual outcomes exist. This is not the case at the present date for vines for instance.

Anticipating increased digitization As digital tools become more prevalent, moral hazard issues should become less stringent and expertise less costly. Interestingly, more complex crop insurance policies will become feasible, that would be conditional to specific cultivation practices and could base indemnification on both expert assessment and indices. This should be anticipated by public authorities as it will open new opportunities, especially if subsidies are made available for the most ecologically friendly insurance contracts.

Appendix

A. The new French crop insurance system

The specific perils covered by CAP-supported insurance in France are officially outlined in a ministerial decree (Décret n° 2016-1612). This exhaustive list comprises drought, extreme temperatures, heatwaves, sunburn, low temperatures, insufficient solar radiation, cold snaps, frost, excessive moisture, hailstorms, snowfall or frost accumulation, storms, tornadoes, and sandstorms. Moreover, insurers have the flexibility to include additional perils, such as lightning.

The system was reformed in 2023, following a consensus on the defects of the previous set-up. The 2005 CAP-supported insurance has indeed not proved attractive enough. Subscription remained quite low despite a high public subsidization rate (Enjolras & Sentis, 2011; Enjolras et al., 2012; Koenig et al., 2022). In France, only

[11] The two predominant variants of US revenue insurance policies are Revenue Protection (RP) and Revenue Protection with Harvest Price Exclusion (RP-HPE). These two options diverge in the method used to calculate the guaranteed revenue. RP takes into account the higher of either the projected price or the price at harvest time, while RP-HPE solely relies on the projected price.

[12] In the US, farmers with more diversified production can subscribe to the Whole Farm Revenue Protection (WFRP) program, which was launched in 2015 to further enlarge the pool of insured farmers.

about 30% of farmers hold a policy insurance (Koenig et al., 2022), and this figure drops to 18% for wine-growers, who are not eligible for some forms of indemnity.

In the spring of 2021, an unprecedented frost wave swept across France, and many farmers were without insurance coverage. Most affected farmers received exceptional public compensation by the National Agricultural Risk Management Fund. In theory, only non-insurable weather-related hazards could be eligible for it. But the Ministry of Agriculture exceptionally suspended the exclusion of vines from this compensation.[13] This exemption is an example of the "soft-budget constraint," whereby public authorities do not respect their commitments not to help out private actors when adverse events happen. This lack of commitment power of the State lessens the incentives for farmers to subscribe to private insurance.

French deputy Frédéric Descrozaille issued a report on July 27, 2021, summarizing the proposals of a public working group mandated by the Ministry of Agriculture on how to reform the calamity indemnity system and boost private crop insurance uptake (Descrozaille, 2021). The new regime (March 2022 law) simplifies the insurance scheme and provides a stronger commitment to reduce compensation for farmers who do not privately insure. One specificity of this regime is that it adjusts (upward) public indemnity payments in case of recognized calamities for farmers who hold crop insurance. The modalities of this recent French reform, composed of a 3-tier system, are both explained in detail and analyzed by Rozan and Spaeter (2024).

Acknowledgements This work was supported by VitiREV, a project led by the Nouvelle-Aquitaine Region and financed by project promoters and the Programme d'Investissements d'Avenir (via the Banque des Territoires as part of the "Territoires d'innovation" call for projects) and was also supported by Eco-Phyto ARRUP-VICO and under grant 20-PCPA-0010 (VITAE). C. Aubert benefited from funding from ANR - Investissements d'Avenir under grant ANR-17-EURE-0010 (TSE) and IdEx université de Bordeaux / GPR HOPE.

Author Contributions C.A., Y.R., and M.R. contributed equally to all steps necessary to write this article. N.P. contributed to writing the first draft.

Declarations

Conflict of interest The authors declare no competing interests.

[13] All climatic risks to vine have indeed been defined as insurable by the Order of 29 December 2010 establishing the list of risks considered insurable for the management of the National Agricultural Risk Management Fund, NOR: AGRT1026964A).

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