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ARTICLE

Effects of flood-induced financial stress on the viability of a cooperative production system and its farmers: A multilevel study

David Nortes Martínez[1] | Frédéric Grelot[1] | Pauline Brémond[1] | Stefano Farolfi[2] | Juliette Rouchier[3]

[1]G-EAU, Univ Montpellier, AgroParisTech, BRGM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France

[2]CIRAD, UMR G-EAU, Montpellier, France

[3]LAMSADE, CNRS, PSL (Université Paris-Dauphine), Paris, France

Correspondence
David Nortes Martínez, G-EAU, Univ Montpellier, AgroParisTech, BRGM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France.
Email: david.nortes-martinez@inrae.fr

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Abstract
Floods can severely disrupt agricultural activities. When these activities are part of production chains, domino effects can occur. We use agent-based modeling to simulate the production dynamics of a French cooperative winery as an example of a production chain, adopting a dual individual-collective perspective. The cash-flow analysis shows that there are nonexplicit mechanisms in the cooperative organization that allow the propagation of flood impacts throughout the chain and influence the winegrowers' ability to cope, thus threatening the continuity of the winegrowers' activity and the cooperative winery itself.

KEYWORDS
agricultural cooperative, cash flow analysis, flood damage, vulnerability

JEL CLASSIFICATION
Q13, Q14, Q54, Q25

1 | INTRODUCTION

Flood risk management measures such as floodplains and water retention areas incorporate a spatial dimension to flood risk management practices. By giving more "lateral space" to the river, these measures help to prevent, regulate and mitigate water-related hazards to better protect stakes downstream such as urban and industrial areas. The implementation of these measures may increase the flood frequency and the exposure of agricultural lands and rural inhabited areas close to the river banks in their place of implementation (Erdlenbruch et al., 2009; Hartmann & Driessen, 2013; Penning-Rowsell et al., 2013).

Because agribusinesses and agricultural activities are critically linked to land productivity and vulnerable to shifts in income and cash flow (Barry & Lindon, 2001), agricultural activities in floodplains and water retention areas can be severely compromised (Pivot & Martin, 2002). Moreover, as local agribusinesses are increasingly linked in production chains—either directly or as a part of cooperative or firm-type organizations—local flood impacts can quickly become regional, national, or transnational. Indeed, natural hazard-related disruptions in production chains and production networks seem to have increased in recent decades (Wenz & Levermann, 2016). This has led to a growing interest in studying their ability to withstand the upheavals and to return to predisruption states (Brusset & Teller, 2017; Kim et al., 2015).

Works on business demises induced by or following natural hazards are scarce (Adekola & Clelland, 2020), and the few existing studies tend to focus on very specific single events and on identifying postdisaster factors of business demise or recovery (Brown et al., 2015; Graveline and Grémont, 2017; Marshall et al., 2015; Nicholas & William, 2012). There is also a lack of research on the interactions of factors and mechanisms that drive business failures following natural disasters, as well as on the potential consequences of business failures across production chains and networks.

We therefore have limited knowledge of how businesses in general, and agricultural activities in particular, would be individually affected by flood hazards and how the impacts they might suffer may affect the production chains in which they are integrated (Bubeck & Kreibich, 2011; Penning-Rowsell et al., 2013). This limited knowledge can lead to misrepresentation of impacts, costs, and even benefits over time and space and can misguide cost–benefit analyses and risk and vulnerability assessments in the context of flood management policies and strategies.

Our work proposes to study the dynamics of production in a production chain following flooding events using a dual level of analysis—individual and collective—so that both the demise of individual businesses and the impact on the production chain can be addressed simultaneously. Specifically, we seek (i) to evaluate to what extent individual agribusinesses integrated into a production chain may be driven to the point of lack of profitability in the aftermath of flood events; (ii) to evaluate to what extent individual demises threaten the viability of the production chain; and (iii) to understand the potential interactions between both levels of analysis.

Our work focuses on agricultural cooperatives, specifically on the French Cooperative Winemaking System (CWS). A very common organization in France, they can be considered as an encapsulated production chain as they integrate several, sometimes all, steps of the production process (Tortia et al., 2013). These organizations have traditionally been used by small-scale farmers as a defense mechanism against market and institutional rigors (Candemir et al., 2021; Chevet, 2004), and because of their distinctive organizational features, they have been considered by some authors as a distinct type of economic organization (Candemir et al., 2021; Cook et al., 2004; Soboh et al., 2009).

Our analysis of the CWS as a production chain builds on the work of Nortes Martínez et al. (2021). Their work uses the conceptualization of the CWS as a production chain to examine the effect that considering explicit interactions (in the form of information flows) among elements in the CWS has on flood damage estimation compared to a baseline scenario in which no explicit interactions are considered. In contrast to Nortes Martínez et al. (2021) who focus on system-level-damage, in our work, we take full advantage of the dual focus of the method to go one step further and analyze the ability of both individuals and the system as a whole to absorb the disruptions of flood events from a financial point of view, using their scenario of explicit interactions. Moreover, the analysis of the individuals and their interactions allows us to uncover mechanisms of impact diffusion hidden in the rules that govern the system.

The article is organized as follows: Sections 2 and 3 describe the production chain and our method, respectively. Section 4 details the experimental design we followed to obtain the results we present in Section 5. The discussion of these results and our conclusions can be found in Section 6. Extensive additional material is available for Sections 3–5.

2 | THE PRODUCTIVE CHAIN

As stated above, the French CWS can be seen as an encapsulated production chain that integrates several steps of the production process.

In the CWS, two different types of operators interact: a winery and a collection of winegrowers (affiliated with the said winery). The latter provides the basic commodity for the production chain (grapes), while the former integrates the remaining production chain stages (fermentation, bottling, and marketing) for its affiliated winegrowers. Both the winegrowers and the winery are, therefore, interdependent in terms of production and revenue generation. In addition, as a production chain, the CWS has several distinctive characteristics: First, costs, revenues, and ownership of the winery's assets are mutualized among the winegrowers so that the winery operates at its break-even point, that is, zero-profit. Second, it is highly dependent on the individual performance of its members to ensure a final quantity of product. Third, it has very limited potential for input substitution. Finally, it may include nonexplicit mechanisms of impact propagation in its mutualization rules.

3 | METHOD

To carry out the multilevel analysis, we consider that it is advantageous to approach the study of the CWS as a complex system (Brémond et al., 2013; Choi et al., 2001), that is, as an ensemble of heterogeneous entities interacting with each other according to a given topology or network of relationships. This approach allows us to analyze the system from the individual to the group, also considering the linkages that govern the interactions of entities, which may allow the appearance of indirect effects throughout the network (Kim et al., 2015). Moreover, some works have shown the importance of factors such as the nature and location of the nodes in the system, the links between them, and the direction of the relationships in analyzing the potential propagation of disruptions within the production chain (e.g., Bode & Wagner, 2015; Haraguchi & Lall, 2015; Nortes Martínez et al., 2021).

To implement our approach, we use agent-based modeling. Agent-based models (ABMs) are computational tools for describing and dynamically simulating systems in which both interactions and heterogeneity of entities must be considered. ABMs can be spatially explicit (Dibble, 2006; Gilbert, 2008) and can be used as *computational laboratories* for the ex ante evaluation of the behavior of systems to controlled changes in key parameters (Bruch & Atwell, 2015). In this work, we take full advantage of the ABMs as virtual laboratories to test the ability of the CWS to generate profitability in the aftermath of flood events. A diagram of our method is included in the Supporting Information Material S2.

3.1 | The COOPER model

The core of our method is the COOPER model (Nortes Martínez, 2019; Nortes Martinez et al., 2021, 2023). This model serves as a *computational laboratory* for the ex ante analysis of the impacts of floods on individual income and expenditure flows among the winegrowers in a CWS.

We briefly describe the model in the following subsections. A full description of the COOPER model following the ODD protocol can be found in the Supporting Information Material S1.

3.2 | Model overview

The COOPER model uses a tree-type topology (Wilhite, 2006): all elements are connected to each other through a central element. This type of topology corresponds exactly to the CWS, where the winery connects and is connected to all the winegrowers, and also each winegrower is connected to his plots.

There are two types of agents: winegrower agents and winery agents. A winegrower agent is defined by the ensemble of a set of plots and a winegrower building. A winery agent corresponds to the winery building.

The model is spatialized, that is, elements are located in a territory which is divided into flood-prone and nonflood-prone areas. The position assigned to each element determines whether the can be directly impacted by a flood (see Supporting Information Material S1, ODD description for more details).

Both the winegrower agents and the winery agents are modeled with reactive behavior. This hypothesis is sustained by information collected through interviews with professional winegrowers and winery managers (see Supporting Information Material S1, ODD for more details). This means that, in the absence of flooding, agents are assumed to be in their optimal performance path so they just follow their schedules. In case of being hit by a flood, both agents will seek to return to their preflood status to ensure their livelihood.

3.3 | Operational productive process in the COOPER model

The production process is actively conducted by both winegrower agents and the winery agent. Both have simplified and seasonally adjusted versions of their own real schedules, linked to the biological cycles of the vine. The coexistence and interaction of these calendars provides the overall internal schedule of the model.

Winegrower agents perform year-round viticultural tasks on their plots. Winegrower agents should also reinvest in their plots (replant) every certain period of time. This has two different consequences for the production process: First, replanted plots are assumed not to be immediately productive; winegrower agents therefore have heterogeneous and lower-than-the-potential productions. Second, there is a rotation between productive/unproductive plots.

The winery agent produces and markets wine. It receives the grapes from its affiliated winegrowers in the fall, turns the grapes into wine during the winter, and sells the wine in the spring (the entire year's supply). Revenues from the sale minus the wine-making cost are shared proportionally to the amount of grape supplied by each winegrower agent (Touzard et al., 2001). In addition, each winegrower agent should cover various outflows, such as his own winegrowing costs, taxes, loan annuities, interest or his own remuneration. Overdrawing situations are penalized: they generate additional payments in the form of interest on the overdrawn amount. Replacement investments are always covered by subsidies and loans—under specific, constant conditions.

3.4 | Effects of floods in the CWS within the COOPER model

Floods cover different extents of a floodable area in a specific season. When a flood hits the CWS, it can cause material damage and agent misperformance, altering the expected flow of inputs, outputs, and cash in the system. Flood impacts result from the combination of seasonal, biophysical processes, and agents' coping/recovery actions (Brémond et al., 2022). These impacts can simultaneously affect plots, winegrowers, and wineries, and their nature depends on both the entity and the season.

Material damage to plots is threefold: (i) damage to soils, considered independent of the season; (ii) damage to yield, dependent on the season; and (iii) damage to plants, stochastic and dependent on the season. When plants in plots are destroyed, the entire yield of that plot is lost. Moreover, it is necessary to replant, and replanted plots remain unproductive for 5 years (with the consequent effects that it will have over the different flows on the system).

Winegrower agents who own plots whose yield has been destroyed by a flood, benefit from savings in winegrowing costs (Brémond et al., 2022). Whether by plant destruction or by direct damage in yield, once the plot loses all of its yield, the owner stops performing winegrowing tasks in that plot and saves the cost of the remaining tasks. There may also be damage to the winegrowers' buildings and equipment. In the model, a building and the farming equipment inside are considered a single unit. When impacted, both the building and the equipment must be repaired (the value of the damage is constant). Until these repairs are completed, both building and equipment lose part of their functionality, causing the winegrower agent to underperform during the season. Ultimately, depending on whether the winegrower agent have access to external help (external coping tactic) or not (internal coping tactic), building damage leads to increased costs or reduced production respectively (see ODD description in Supporting Information Material S1).

In the case of the winery agent, both material and immaterial damage result from flood impacts on its building and equipment. The material impact concerns the building and equipment (again considered as a single unit), as well as the stocks of wine/grapes present in the building from autumn to spring. When the building is impacted by the flood, reparations should be made, and if there are stocks of wine/grapes, they are completely lost. In terms of performance, when the winery agent is flooded, depending on the season it gets impacted, grape collection, wine production or wine marketing may not be performed, therefore the entire production may be lost. In this case, part of the wine production loss is covered by insurance. Repairs not covered by the winery agent's insurance are financed through loans. These loans are ultimately repaid by the members of the winery agent. Loan annuities therefore increase the winery agent's structural costs. Since all costs are shared among the members, a loan to the winery agent increases the operational outflows of each winegrower agent in the CWS.

3.5 | COOPER model's output and financial analysis

The output of the model is summarized in Table 1. Cash flows for each individual winegrower agent are simulated based on Lawson's identity (Sharma, 2001), as shown in Equation (1).

$$\begin{aligned} &\pm NCFO_t - T_t \pm CFF_t - CFI_t = \\ &= R_t - C_{vg_t} - C_{wm_t} - T_t - FO_t - OR_t + FI_t - I_t = \\ &= \pm Tr_t \end{aligned} \tag{1}$$

We focus on the cash flow analysis for two main reasons. First, the monetary valuation of cash flows over time, combined with accounting conventions and methods, is a common practice in microeconomic approaches (Bubeck & Kreibich, 2011; Penning-Rowsell et al., 2013). Second, cash flow analysis is widely used to anticipate corporate financial distress because (i) it helps avoid accrual accounting deficiencies; (ii) business performance is intrinsically linked to cash inflows and outflows (Sharma, 2001); and (iii) it only captures transactions where cash actually changes hands. Furthermore, cash flow analysis can be used to assess the financial viability of each individual winegrower and the CWS as a whole.

3.6 | Financial viability criteria

To conduct the financial viability study, we need to establish a viability criterion for each level of analysis.

TABLE 1 Monetary flows simulated in the COOPER model to elaborate the analysis of cash flow.

Metric	Key variable	Cash flow	Classification[a]
Farm revenues from wine selling	R_t	NCFO	inflow
Vinegrowing costs	C_{vg_t}	NCFO	outflow
Winemaking costs	C_{wm_t}	NCFO	outflow
Loan annuities	FO_t	CFF	outflow
Overdrawing penalization	FO_t	CFF	outflow
Profit taxes	T_t		outflow
Owner remuneration[b]	OR_t	CFF	outflow
Loans	FI_t	CFF	inflow
Subventions	FI_t	CFF	inflow
Replacement investments	I_t	CFI	outflow
Treasury	Tr_t		inflow/outflow

Note: All indicators are measured in euros (€).

Abbreviations: CFF, cash flow of financing activities; CFI, cash flow of investing activities; NCFO, net cash flow of operations.

[a]From the winegrower point of view.

[b]We consider the owner's remuneration in the Cash flow of Financing activities, thus assimilating it as the dividend paid to shareholders (so far, the winegrower is the only shareholder of his own exploitation). If that remuneration were considered part of the operational costs it should be included in the Net cash flow of operations.

3.6.1 | Individual level criterion

At the individual level, we combine the notion of financial default with the notion of viability in Desbois (2008). Thus, we consider a winegrower to be in a situation of financial distress when he is unable to meet payments and/or contractual obligations on time. In addition, winegrowing activities cannot be considered viable if they are not able to (i) provide the owner with a minimum amount of money that ensures his subsistence, and (ii) remunerate the rest of the productive factors (labor and capital). Thus, to be financially viable, the winegrower should be able to meet loan payments and remunerate all factors: interest and salaries including his own.

3.6.2 | System level criterion

At the system level, we establish a *systemic restructuring threshold* (SRT), that we define as the minimum number of winegrowers that must cease their activity to cause the remaining ones to reach their break-even points. In the CWS, winegrowers share the ownership of the means of production and mutualize the costs of wine production and marketing carried out in the winery (wine-making costs hereafter). The mutualization of costs is carried out according to specific rules. These rules expose individual winegrowers to cost variations due to variations in the production of other winegrowers (a mathematical demonstration is included in the Supporting Information Material S2). Cessations of individual winegrowers reduce the amount of production in the CWS, increasing the costs of the remaining winegrowers and decreasing their profit rate (ceteris paribus). Therefore, above the SRT the system does not provide incentives for winegrowers to stay in the system, and restructuring must take place to ensure the continuity of the system.

To determine the SRT, we use the COOPER model to calculate the cash flow dynamics of a hypothetical *average winegrower agent* and a hypothetical *average system* in the absence of floods.

We then sequentially reduce the number of winegrowers (hence the productive surface and the production) in the system at a fixed rate and recalculate the wine-making cost. We evaluate the effect of the new wine-making cost share on the profit of the *average winegrower agent*, whose production (hence revenue) remains unchanged. The number of winegrowers that need to cease their activities to provoke that the average winegrower reaches its break-even point is identified as the SRT. Both the magnitude of the change in the individual share of wine-making costs and the SRT are related to the flexibility of the winery's cost structure. Due to the cost-sharing rules used in the CWS, the SRT depends on the ratio fixed-to-variable cost in the winery (a mathematical demonstration is included in the Supporting Information Material S2). In Figure 1, we illustrate this dependency. We define the parameter $\lambda \in [0, 1]$ as the measure of the flexibility of the winery agent's cost structure: High values of λ represent rather rigid cost structures with a high proportion of structural cost. As the figure shows, the SRT and the flexibility of the winery agents's production costs have an inverse relationship. Low degrees of flexibility shift the SRT downwards in comparison with higher degrees of flexibility. Thus, rather rigid cost structures are expected to reduce overall system's ability to absorb production shocks.

The combination of these two criteria allows us to assess whether the system would be able to withstand the financial consequences of a flood event as a result of the ability of individuals to cope: At the individual level, if the cash flow analysis indicates that the winegrower agent does not meet the viability criterion, the winegrower agent is considered bankrupt, ceases his activity and exits the system with all of his plots. The total number of demised winegrowers is compared to the SRT. If the number of demises reaches the SRT, the system is considered "in need of restructuring" (an example is provided in the Supporting Information Material S2).

4 | EXPERIMENTAL DESIGN

The experimental design consists of four experiments focusing on four system parameters, which are important for assessing the system's performance during flooding.

The first experiment tests the effect of flooding over the winery. In the CWS, wineries act as hubs, connecting all winegrowers and centralizing production, storage, and marketing. Thus, the CWS relies on the proper performance of the winery to ensure the smooth functioning of the system. Our experimental design sets up two alternative cases: one where the winery agent is safe (e.g., a winery that has been

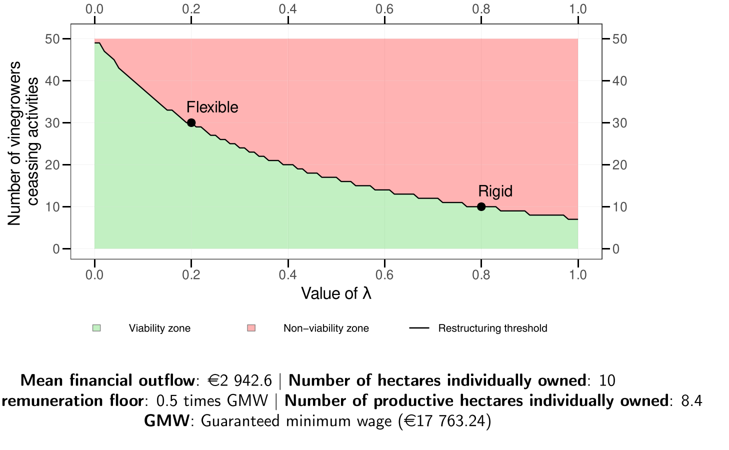

FIGURE 1 Minimum number of business cessations within the system necessary to make remaining business reach their break-even points. Calculations in relation to the winery's cost structure flexibility (λ) and based on the system's average winegrower values.

adapted to avoid flood damage or is located outside the flood area) and one where the winery agent is flooded (e.g., a winery located inside the flood area without efficient adaptation measures).

The second experiment tests the effect of variations in the rigidity of the winery's cost structure. As noted, the SRT and the magnitude of variations in the individual shares of wine-making costs are related to the flexibility of the winery's cost structure (λ). We set two values for the parameter λ: a rather flexible structure, represented by $\lambda = 0.2$ (based on calculations from Folwell and Castaldi, 2004), and a relatively rigid structure, represented by $\lambda = 0.8$ (using data from CER France, 2017).

The third experiment tests the effect of the variations in the amount of cash resources available to winegrowers. Based on data from the Farm Accountancy Data Network (FADN, 2022), we set five values for the winegrower agents' initial treasury: €0, €250, €500, €750, and €1000 per hectare owned.

The fourth experiment tests the effect of the creditors' confidence. To represent the creditors' trust we use the time of demise as a proxy, and we set two different times. The first establishes that as soon as the winegrower agent does not have enough resources to cover his outflows, the activity ceases (*no-trust* case). The second establishes a scenario in which the winegrower agent benefits from a margin of up to 5 years (based on Sharma, 2001) to recover from losses before ceasing the activity (*trust* case), thanks to an implicit level of trust and solidarity from his creditors.

The four experiments share a common setup to ensure the comparability of the simulations: one winery agent, 50 winegrowers and 500 plots of 1ha each. Ten out of the 50 winegrowers and 150 out of 500 plots are located in the flood-prone area (see Supporting Information Material S1, the ODD description for configuration plausibility). The number of entities in the flood-prone area increases linearly with the distance from point 0, where the river is located. Each winegrower agent owns 10 ha, 30% of which are randomly distributed along the flood-prone area. Individual growth investments are not allowed, so winegrower agents remain the same size throughout experiments. The spatial location of entities and the links between them is kept constant throughout experiments. This ensures that direct impacts always affect the same entities so that observed differences can be traced back to changes in parameters. The plausible minimum winegrower agents' individual remuneration is set at 50% of the French guaranteed minimum wage (GMW), that is, €8881.62, which implies a remuneration floor of 5% of the GMW per ha owned (CER France, 2014). Finally, to finance their investments, winegrower agents are assumed to borrow money from financial institutions. It is assumed that creditors always lend the money and that they offer homogeneous conditions to all winegrower agents.

The experimental design considers flood events that successively cover larger extents of the flood-prone area in the interval [0, 100]. Flood events are simulated once a year during the first year of simulation. To account for a potential seasonal effect of flood events due to plant cycles and production processes, flood events are simulated once per season. As a convention, the flood event is assumed to occur at the beginning of the season. When flooded, winegrowers use the internal coping tactic (see Supporting Information Material S1, ODD description), that is, winegrowers do not have access to external services/help.

Regarding simulations, each 2-tuple flood-season is simulated 50 times to account for the stochastic processes in the model's damage functions. The difference between the most and the least impacting repetitions in terms of plots destruction stands as a measure of the scenario's uncertainty. The total number of simulations run reaches 57,600. Tables summarizing our experimental design are provided in the Supporting Information Material S2.

5 | RESULTS

The results of our simulations are summarized in Figures 2 and 3. They show the flood extent at which the system reaches the SRT by season, amount of initial treasury, degree of flexibility of the winery agent's cost structure, and cessation time horizon. Green areas indicate all flood extents

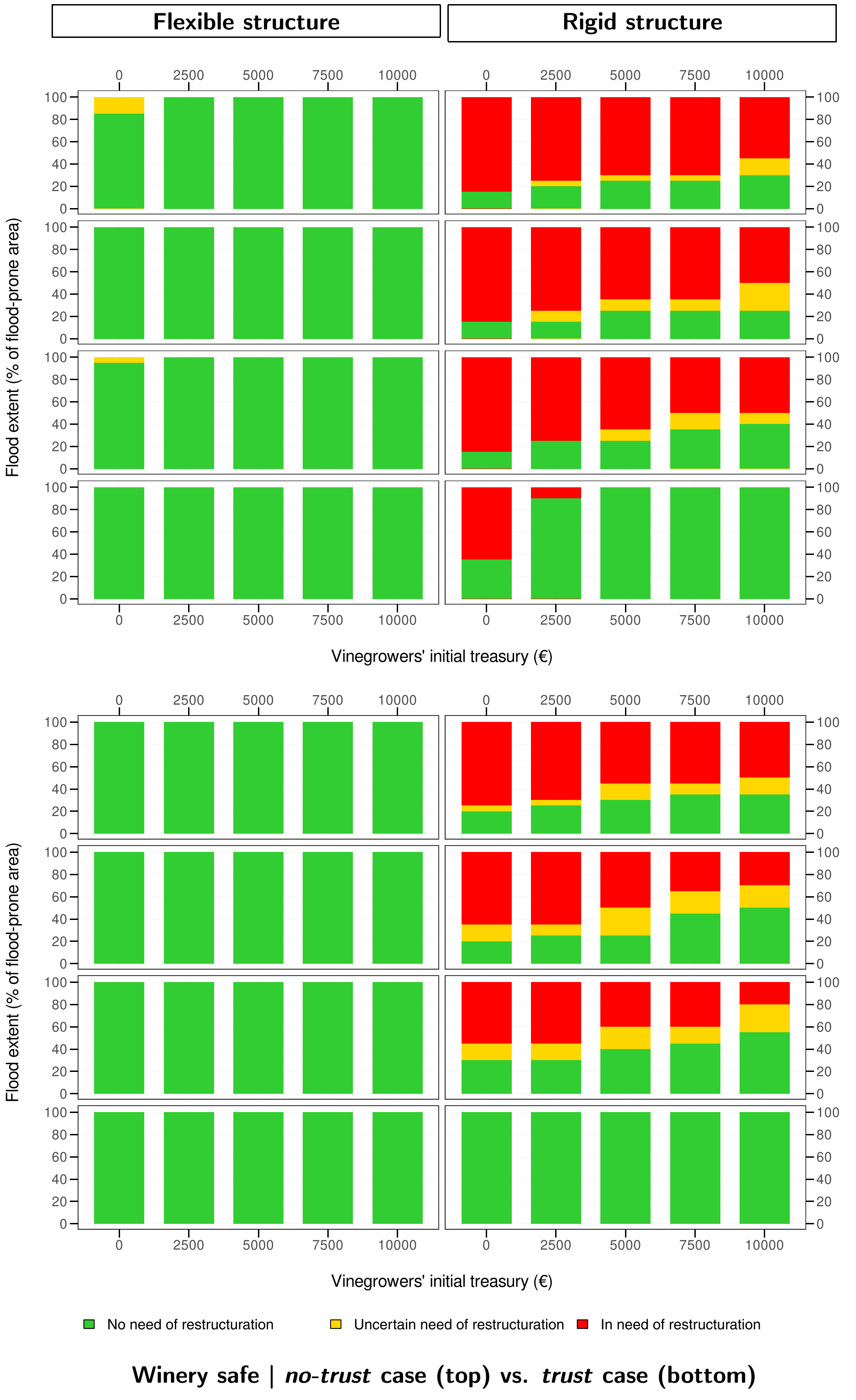

FIGURE 2 Minimum flood extent necessary to reach the restructuring threshold (SRT) by winegrowers' initial treasury and rigidity of the winery's cost structure.

where the system is able to withstand the effects of the flood without reaching the SRT despite losing members. Conversely, red areas mark flood extents at which the system reaches the SRT, that is, it must be restructured to ensure its survival. Yellow areas mark those flood extents where at least one of the iterations reached the SRT.

5.1 | Experiment I: Effect of the flooding over the winery

In a system with a topology like the CWS where the system's performance is highly dependent on the correct performance of the central agent, a flood over the winery agent is critical for the system (Figures 2 and 3). Furthermore, the impact of flooding events has a seasonal effect as schedules evolve throughout the year.

Flood events in winter, spring, and autumn disrupt the winery agent's production, marketing, and storage operations, respectively. Since each of these activities is essential to the winery agent's annual revenue, once the winery agent is flooded, the system collapses regardless of insurance (Figure 3). The loss of revenue added to the increase in annual operational outflows due to the winery agent's loans for repairs drive all winegrower agents into a situation of financial default, regardless of their particular situation. Spring floods would be notably arduous as the entire production process is completed, so the full wine-making costs should be added to production losses.

Summer floods do not affect any of the key production tasks in the winery agent. Thus, there is no impact on production resulting from the impact on the winery agent. However, flood damage must be repaired and, as a result, the winery agent's loan annuities will increase, reducing the winegrower agents' net cash flow from operations, which, in turn, will increase the number of business cessations. Summer floods pose a threat to the CWS only if the winery agent's cost structure is rigid ($\lambda = 0.8$). In such a case, rather small flood events push the CWS towards the SRT.

5.2 | Experiment II: Effect of the degree of flexibility of the winery's cost structure

This experiment contrasts a flexible cost structure—very responsive to changes in production— with a rigid cost structure—practically unresponsive to changes in production—and examines the effect on business demises. The effect is shown in Figures 2 and 3 by comparing left and right sides.

The simulations show that in addition to lowering the SRT, rather rigid production cost structures in the winery agent increase the number of business cessations. The interaction of these two effects reduces the capacity of the system to absorb the impact of floods. As Figure 2 shows, a relatively flexible cost structure ($\lambda = 0.2$ in Figure 1) in the winery agent barely causes the system to reach the SRT, while a rigid cost structure ($\lambda = 0.8$ in Figure 1) implies that relatively small flood extents (between 20% and 50% of the flood-prone area) cause the system reach the SRT. If the winery agent is flooded (Figure 3), the same effect is observed in the case of spring floods.

In the case where the winery agent is not flooded (Figure 2), seasonal effects are observed due to the different impact of floods on plants, yield, and performance. Higher plant vulnerability in spring results in important losses for winegrower agents whose land is flooded. This damage affects current and future cash flows: production losses affect revenues, while unplanned replanting forces investments that can become a financial burden. During summer and autumn, plant vulnerability to flooding decreases, slightly reducing the likelihood of crop damage, hence revenue losses or failing investments. In winter, plant vulnerability continues to decrease, further reducing the likelihood of crop damage and thus increasing the system's capacity to withstand the consequences of flooding.

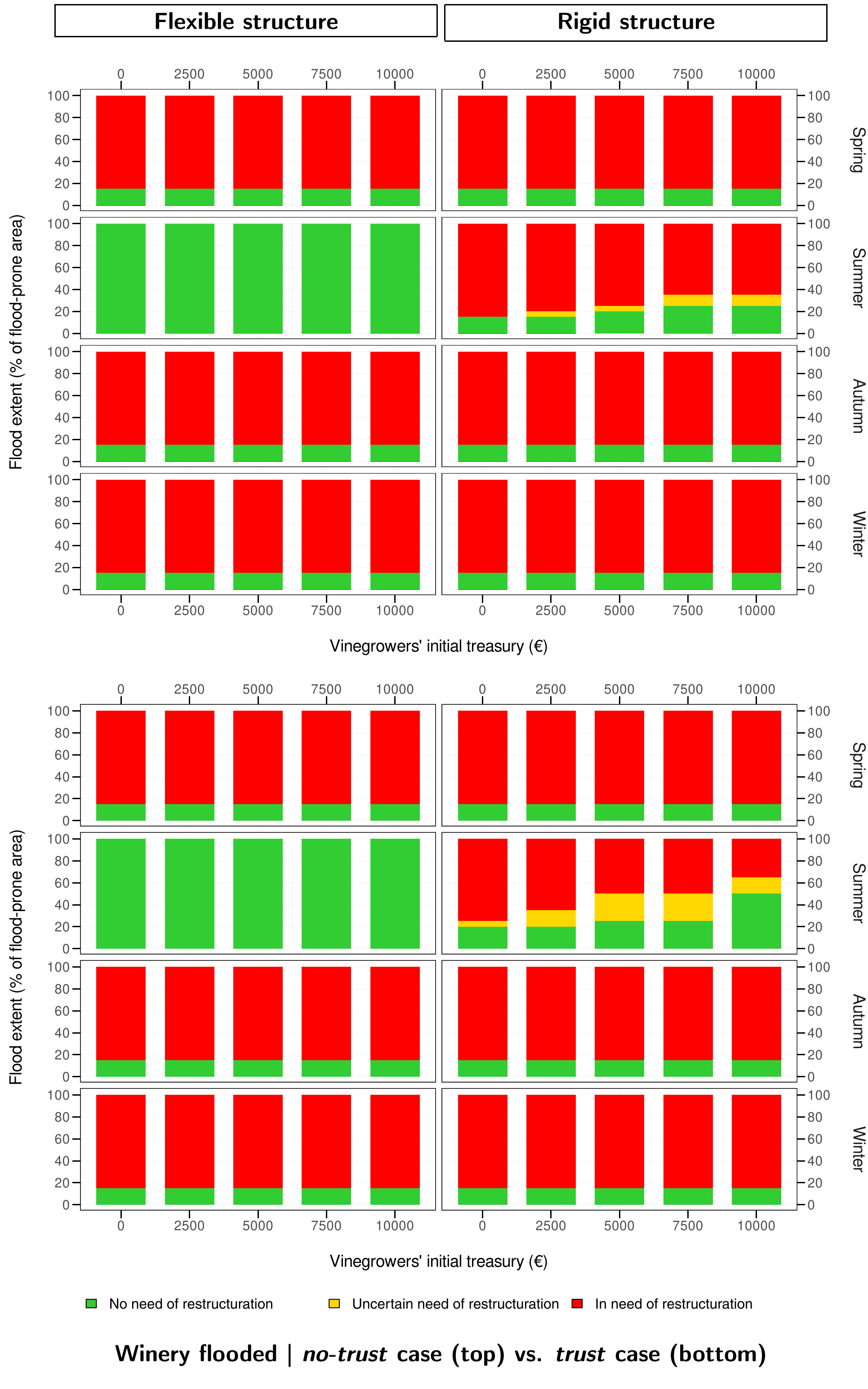

FIGURE 3 Minimum flood extent necessary to reach the restructuring threshold (SRT) by winegrowers' initial treasury and rigidity of the winery's cost structure.

5.3 | Experiment III: Effect of the amount of available cash resources of winegrowers

This experiment sets different amounts of initial treasury for each winegrower agent and analyzes the effects on the number of business demises and the system's ability to cope with floods. The initial treasury is set homogeneously for all winegrower agents, that is, they all start the simulation with the same amount. The effect is shown in Figures 2 and 3 along the x-axis.

The effect of this parameter on business demises is fairly intuitive: an increase in the initial treasury increases the capacity of the winegrower agents to absorb the negative consequences of floods, thus ensuring their survival. From a system perspective, reducing the number of business demises improves the capacity of the system to withstand the consequences of floods, moving it away from the SRT. Our results show that increasing each winegrower agent's initial treasury from €0 to €10,000 allows the system to withstand floods 10%–65% larger in extent (Figure 2). Our results also show that, from a system perspective, the relevance of this parameter is closely linked to other parameters. When the winery agent is not flooded, larger treasuries help the system's coping capacity, but to a lesser extent than ensuring flexible costs structures in the winery agent. If the winery agent is flooded in one of the key seasons of the production process, the initial treasury size has no significant effect.

Seasonal effects are also observed when considering this parameter. Spring, summer, and autumn follow a similar pattern, although the effect of increasing the initial treasury on the system's capacity to cope seems to be more intense in autumn than in summer or spring. In winter, a small increase in initial treasury significantly improves the system's ability to cope with floods (Figure 2-top).

5.4 | Experiment IV: Effect of the creditor confidence

This experiment considers two alternative cases: *no-trust*, in which winegrower agents cease operations as soon as they default on their payments; and *trust*, in which winegrower agents have up to 5 years from the moment they default on their payments to try to keep their operations going. The effect is illustrated in Figures 2 and 3 by comparing top and bottom graphs.

Creditor confidence and initial treasury have similar effects: when winegrower agents benefit from more confident creditors, the number of demises decreases, which in turn, increases the system's ability to withstand the consequences of flooding (see Figures 2 and 3-summer). For example, focusing on Figure 2, we see how compared to non-trusting creditors (top graph), trusting creditors (bottom graph) help push away the minimum flood extent that would make the system reach SRT.

Either the seasons or the flexibility of the cost structure seem to have a negligible effect on this parameter. In fact, trusting creditors reduce the number of business cessations regardless of the seasons and the rigidity of the winery agent's cost structure. The situation of the winery agent is a different case: if the winery agent is flooded during the key seasons of the production process, creditor confidence has no effect (Figure 3).

Readers can find the figures containing the detailed results as well as an analysis of hard hypotheses of the model and the limits of our analysis are included in the Supporting Information Material S2.

6 | DISCUSSION AND CONCLUSIONS

This paper develops a dual individual/collective perspective in analyzing flood disruptions in a productive chain (the CWS), allowing us to show how a system's capacity to absorb disruptions from a given flood emerges from its components. To do so we use an agent-based model (the COOPER model) that allows us to conduct dynamic analyses of the effects of flood events over a production chain with explicit links between its constituent elements. All of these elements allow us to make several contributions to the field.

First, existing studies on individual businesses highlight the importance of individual characteristics in coping with disruptions (see Marshall et al., 2015). Intuitively, we might think that parameters such as the amount of cash available to winemakers or the confidence of creditors are most important. However, our analyses show that there are mechanisms and factors that allow impacts to propagate throughout the chain that are more relevant in explaining potential production chain collapse. This highlights the importance of the bottom-up approach and the dual focus of the analysis to fully understand: (i) how disruptions propagate through the system; and (ii) how individual characteristics ultimately influence the system's ability to cope with the disruption. From this point of view, the lack of studies on the indirect effects of floods may lead to the overlooking of key factors in the design of flood management policies.

Second, our analysis builds on the work of Kim et al. (2015) and Nortes Martínez et al. (2021) and considers not only the explicit links between the composing entities of the system but also the rules that govern the relations and interactions between entities within the production chain. The explicit consideration of both links and rules within the production chain provides useful insights into the consequences of flood disturbances and the ability of agricultural systems to cope with them. Specifically, it allows us to identify (i) the potential for disturbance propagation; (ii) the intensity with which the disturbance propagates; and (iii) latent mechanisms of compensation. Such a result has strong managerial implications. By preventing cost structures from becoming too rigid or by making already rigid structures more flexible, winery managers can influence the thresholds of the compensation mechanisms, therefore the ability of the cooperative system to absorb shocks and prevent damage from spreading. Winery managers thus count on a contagion management tool. It is worth noting that this contagion management tool would work regardless of the cause of the yield losses since it is based on a specific cost-revenue sharing rule. The scarcity of studies on the specific rules governing cost-revenue sharing rules in agricultural cooperatives makes it difficult for us to foresee how a change in the rule might change our results. More work is needed in this direction.

Our results also show how flooding of specific entities (e.g., wineries) can turn an organization whose *raison-d'être* is the protection of its adherents into a financial trap. This not only highlights the role of these entities as a factor of vulnerability but also has strong implications from a managerial point of view when it comes to adopting flood adaptation measures.

Third, standard practices in cost–benefit analysis and business resilience studies assume that there is a return to a predisaster state. Conversely, our results show that such a return may not be achievable for either individual businesses or the system. In other words, the results obtained challenge the assumption of *return to predisaster states* on which standard practices in cost–benefit analysis base their conclusions. We are aware, however, that the COOPER model, although based on real-world evidence, relies on some strong hypotheses. These include, for example, the complete disruption of production tasks when the winegrowers' or the winery's buildings are impacted, or, in another example, the reactive behavior of winegrowers. These hypotheses are, however based on real-world evidence and could be refined with access to more detailed information on the organization of the production process, including contingency strategies.

From this perspective, even if the evidence gathered supports their plausibility, the results obtained when the winery is flooded should be considered as a worst-case scenario. Real situations are expected to lie between the two cases of flooded and nonflooded winery. Because of their managerial implications, our results could be used as a basis for discussion with cellar managers. First, this would allow us to consolidate the hypotheses used in our analysis. Second, and most importantly, it would enable managers to become aware of the range of possible events that could affect them, to anticipate the strategies that need to be put in place.

Fourth, the fact that we consider the schedule of each agent, albeit simplified, highlights the importance of considering the timing of the flood event in the context of agricultural activities.

Practically all the parameters show a seasonal behavior, with spring floods being comparatively more punishing for the production chain and its winegrowers than summer, autumn or winter floods. In such conditions, the application of general recipes should be parsimonious. It may be relevant to adapt damage prevention and flood management measures to the organization and behavior of the hazard.

Finally, this paper presents findings that exploit the potential of ABMs in the study of disruptions and propagation of impacts within a production chain. Postevent field surveys alone do not allow us to explore events of different magnitudes (important in the context of climate change), nor to explore the full range of impacts that natural hazards can have on a system, which is particularly important in the context of adaptation to climate change. ABMs allow us to trace the triggers, causes, and drivers of impacts and to understand their significance as they propagate through the system. The potential of ABMs to serve as laboratories for ex ante study of the consequences of production chain disruptions caused by natural hazards is enormous, and to contribute to the formulation and research of risk management policies deserves consideration.

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OPEN RESEARCH BADGES

This article has earned an Open Materials badge for making publicly available the components of the research methodology needed to reproduce the reported procedure and analysis. All materials are available at https://entrepot.recherche.data.gouv.fr/dataset.xhtml?persistentId=doi:10.57745/JTNCI8.

DATA AVAILABILITY STATEMENT

The model that supports the findings of this study is openly available in Recherche Data Gouv at https://doi.org/10.57745/JTNCI8.

ORCID

David Nortes Martínez http://orcid.org/0000-0002-0711-5885
Frédéric Grelot https://orcid.org/0000-0003-2638-8114
Pauline Brémond https://orcid.org/0000-0001-7478-1290
Stefano Farolfi https://orcid.org/0000-0003-4712-2497
Juliette Rouchier https://orcid.org/0000-0002-4022-6720

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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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