

Are interactions important in estimating flood damage to economic entities?

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Abstract. Estimating flood damage, although crucial for assessing flood risk and for designing mitigation policies, continues to face numerous challenges, notably the assessment of indirect damage. It is widely accepted that damage other than direct damage can account for a significant proportion of total damage. Yet due to more scarce data sources and lack of knowledge on links within and between economic activities, indirect impacts have received less attention than direct impacts. Furthermore, attempts to grasp indirect damage through economic models have not gone below regional levels. Even though local communities can be devastated by flood events without this being reflected in regional accounts, few studies have been conducted from a microeconomic perspective at local level. What is more, the standard practices applied at this level of analysis tackle entities but ignore how they may be linked.

This paper addresses these two challenges by building a novel agent-based model of a local agricultural production chain (a cooperative winemaking system), which is then used as a virtual laboratory for the ex-ante estimation of flood impacts. We show how overlooking existing interactions between economic entities in production chains can result in either overestimation (double counting) or underestimation (wrong estimation of the consequences for the activity) of flood damage. Our results also reveal that considering interactions requires thorough characterization of their spatial configuration. Based on both the application of our method and the results obtained, we propose balanced recommendations for flood damage estimation at local level.

1 Introduction

Floods are natural phenomena that can cause very serious damage, particularly to economic activities (SwissRE, 2017). Due to the impacts of global warming on hydrological regimes and development of territories exposed to flooding, flood damage is indeed expected to increase in the coming decades (Field et al., 2012). It is thus becoming increasingly important to understand the precise mechanisms through which floods cause economic damage. This understanding will help analyze the development of territories exposed to floods, understand the observed – and guess the expected – reactions of agents to the damage they undergo, and improve the design of flood management policies, especially those involving agents' adaptations (Viglione et al., 2014; Grames et al., 2016; Barendrecht et al., 2017; Grames et al., 2017). It will also be particularly useful to estimate the risk of an exposed territory (risk assessment) and to assess the efficiency

25 of flood management projects, particularly through cost-benefit analyses (Brouwer and van Elk, 2004; Merz et al., 2010; Penning-Rowsell et al., 2013a).

The current way of estimating damage – which may rely on empirical approaches (for example, by examining insurance data), modeling approaches (like damage functions¹), or a combination of the two – is often limited to assessing direct damage to buildings and assets (equipment, stocks, furniture). However, only estimating direct damage frequently leads
30 to underestimating the value of the impact (Field et al., 2012). Indeed, as mentioned by many authors (Scawthorn et al., 2006; Meyer et al., 2012, 2013; National Research Council, 1999), impacts other than the direct material ones do occur and should be estimated as indirect damage. Although there is a consensus on the importance to distinguish between direct and indirect damages, what to include in each category is still the subject of debate. For instance, Merz et al. (2010) consider as direct damage to be the impacts *which occur due to the physical contact of flood water*, and indirect damage
35 to be the consequences of direct damage that occurs *outside the flood event* either in space or time. Meyer et al. (2013) introduced the term *business interruption* for activities that are directly impacted, explicitly restricting direct damage to physical damage, and indirect damage to damage that occurs outside the flood-prone area. Except for the terminology, this is fully compatible with the view of Penning-Rowsell and Green (2000), for whom business perturbation of directly impacted activities is indirect damage, and other business perturbation is named secondary indirect damage. Cochrane
40 (2004) considers business perturbation of directly impacted activities to be direct damage, while indirect damage is any other negative consequences not considered as direct. 

Indirect damage has been estimated using either statistic-based approaches (e.g. Kajitani and Tatano, 2014; Yang et al., 2016) or model-based approaches, notably input-output (IO) models (Hallegatte, 2008; Van der Veen et al., 2003; Hallegatte, 2014; Crawford-Brown et al., 2013; Xie et al., 2012), computable general equilibrium (CGE) models (Xie et al.,
45 2014; Rose and Liao, 2005; OCDE, 2014) or a combination of the two (Donaghy et al., 2007; Rose and Krausmann, 2013; Santos et al., 2014; Hallegatte and Ghil, 2008). Both families have their own strengths and weaknesses. For instance, compared with CGE, IO models are simpler to use and can provide detailed information on economic interdependencies within a regional economy. However they allow neither substitution nor price effects. CGE models are more flexible and able to account for exogenous interventions in the flood's aftermath and changes in supply/demand. Their drawbacks
50 include the absence of technical limits to substitution – even in the short term – and perfect adjustable markets (Koks et al., 2015; Kelly, 2015; Hallegatte and Przulski, 2010; Okuyama and Santos, 2014; Przulski and Hallegatte, 2011). Furthermore, both kinds of models base their calculation of indirect impacts on rather simplistic prefixed coefficients or static ratios of direct damage (Hallegatte et al., 2007; Oosterhaven and Többen, 2017). This method leads to rather large indirect impacts (Oosterhaven and Többen, 2017) and its accuracy needs improvement (Meyer et al., 2013; Kreibich and
55 Bubeck, 2013).

Both kinds of models have been successfully implemented at national and/or regional levels (Bosello and Standardi, 2018; Carrera et al., 2015). However, their potential to provide useful information in decision-making processes when the

¹A damage function is a simplified representation of how an asset is damaged by a flood: it draws a link between flood intensity, measured by parameters such as height or duration, and the damage that would be expected if the given asset is flooded by an event of given intensity.

economic disruptions of floods might vanish before reaching the aforementioned levels is questioned (Green et al., 2011). There has been attempts to adapt the CGE methodology at local level. For instance, Ferrarese and Mazzoli (2018) used a local social accounting matrix to study the impacts of rural development plans in Mexico. But none have been dedicated to flood damage assessment so far. As flood risk management relies on understanding the consequences of floods (Green et al., 2011) – and flood hazards can be disastrous for local communities and production chains – local flood management practices should benefit from locally-focused studies. Indeed, Meyer et al. (2013) underline the importance of improving the knowledge of the link between direct and indirect impacts at microeconomic and local levels.

65 In practice, current methods of estimating flood damage at local and microeconomic level rely on the implicit assumption that economic entities can be treated separately, i.e. without considering how they are interlinked. In concrete terms, damage assessment relies on crossing information on exposure and susceptibility of assets – using geographic information systems (GIS) – that were previously pooled in homogeneous classes (Kreibich and Bubeck, 2013). This practice is appropriate because it fits the way assets are geolocated by GIS and how damage functions are defined. However, to use
70 these approaches at micro level, without considering the links between economic entities, implicitly assumes not taking the disruption of activities outside the flood-prone area into account.

Moreover, many economic entities are made up of different entities – e.g. different establishments, buildings, plots, etc – located in different places, whose exposure to flooding is not the same. In these cases, defining whether such systems are directly or indirectly affected by a flood is not easy: some crucial parts may be directly damaged while others
75 remain safe. Taking this internal organisation into account is rare in damage assessment. It is occasionally done in the agricultural sector (Brémond et al., 2013), but has not yet been extended to other economic sectors. In practice, assessing the disruption of business is based on simplistic models or even static ratios of direct damage, whose accuracy needs to be improved (Meyer et al., 2013; Kreibich and Bubeck, 2013).

In this context, we want to introduce the notion of complex productive systems (CPS). A CPS can be an economic
80 entity whose productive components are located in different places, or a collection of economic entities interacting in a global production process (like a supply chain). Among the frequently disregarded flood impacts, in this article, we focus on economic damage due to disturbance of a production process resulting from interactions between different economic entities that may or may not belong to the same firm.

How production processes at local level are affected by flood hazards has not yet been studied in detail. Neverthe-
85 less, the literature on business recovery and resilience of economic activities introduces interesting elements (Rose and Krausmann, 2013). *Ex-post* analyses of disasters in supply chains were carried out after the 2011 flood in Thailand (Haraguchi and Lall, 2015; Chongvilaivan, 2012; Linghe and Masato, 2012). Among these analyses, Haraguchi and Lall (2015) showed that damage propagation in a supply chain depends on the location of the productive entities and on the links between such entities. The same authors also identify the challenges to a better understanding of the robustness of
90 supply chains, namely, the recognition of critical nodes and links, the identification of the direction of links in these complex networks, and the assessment of the effectiveness of bridge ties. This highlights the need for in-depth understanding

of the production processes involved and characterization of the links between entities to finely estimate indirect damage at local levels.

Local dynamics are best grasped through *bottom-up* approaches (Crespi et al., 2008): by designing the system from the bottom up, we identify the entities of interest, their interactions and the environment in which they take place. This kind of approach requires specific modeling techniques like agent-based modeling (Tesfatsion, 2002; Smajgl and Barre-
95 reteau, 2017; Jenkins et al., 2017). An agent-based model (ABM) is a computational tool for the description and dynamic simulation of complex systems. It relies on the description of a system as a collection of autonomous entities, their interactions with one another and their interactions with the environment in which they are embedded (Smajgl and Barre-
100 reteau, 2014). Additionally, ABMs allow explicit spatial distributions (spatialized models) and time dynamics at different orders of magnitude. ABMs can also be used as complements to other modeling techniques (Jansen et al., 2016) which may help to overcome at least some of the criticisms that IO and CGE models have received. However, even though ABMs are a promising way to improve the estimation of flood impacts (Safarzyńska et al., 2013; Meyer et al., 2013), to date, applications are rare.

105 In this article, we tackle the following question: To what degree can modeling interactions within or between economic entities improve flood damage estimation compared to current approaches that do not take any of these interactions into account? To do so, the article is organized ~~in eight into 6~~ sections. Section 2 briefly describes the ~~interest of rationale for~~ choosing a cooperative winemaking system (CWS) as a case study of CPS as well as the CWS itself and our data sources. ~~Section 3.2 presents~~ ~~In section 3, we give an overview of our methodology (subsection 3.1), present~~ the model
110 we developed to analyze ~~how the CWS is impacted by floods. In section 3.1 we present both~~ the ~~impact of flooding on CWS (subsection 3.2), and present the~~ setup and protocols followed in the experiments we conducted (subsection 3.1). The results obtained in our experiments are presented in ~~sections 4.2 and 4.1~~ ~~section 4, with a presentation of the damage estimate for the current practice (subsection 4.1), the influence of introducing interactions (subsection 4.2), and the influence of the configuration of these interactions (subsection 4.1).~~ Section ~~5.3 contains a brief summary of 5~~ ~~discusses~~
115 ~~our main results and~~ the main limits of our analysis, and our final conclusions can be found in section 6.

2 Case study and data collection

2.1 The cooperative winemaking system as a case study of complex productive system

Flood and agriculture

120 In monetary terms, flood damage to the agricultural sector rarely represents the biggest share of total flood damage. Yet, there is a practical interest in comparing existing ways of estimating damage with those that take interactions within the agricultural sector into account. There are three main reasons for this interest. First, the fact that the damage to agriculture is relatively less important is offset by the fact that agricultural areas may be chosen as targets for floods to protect urban areas (Erdlenbruch et al., 2009; Brémond et al., 2013), meaning agricultural areas may be negatively impacted. A thorough understanding of how the agricultural sector is damaged is thus crucial when designing compensation schemes

125 due to such risk transfers (Erdlenbruch et al., 2009). Second, the agricultural sector often involves interactions between
different economic entities (e.g. farms, suppliers, equipment suppliers, food processing companies, traders). Character-
izing the internal organization of these entities is consequently important to accurately estimate how floods affect their
activity, even at the level of individual farms (Posthumus et al., 2009; Morris and Brewin, 2014). Finally, Hess and Morris
(1988), Morris and Hess (1988) and, more recently, Brémond and Grelot (2012) proposed methods to estimate loss of
130 business by modeling agricultural production systems considering the links between the productive components of a farm
(cattle and grassland, agricultural plots and buildings, etc.). This approach, although rare (Brémond et al., 2013) and not
yet extended to other economic sectors, merits further exploration.

2.2 The cooperative winemaking system

Our study is based on two case studies in southern France, where so-called cooperative winemaking systems (CWSs)
135 are very common.

A CWS is a CPS in which two types of economic agents interact: winegrowers (aka farms) and a winery. The coop-
erative character of the system defines the shared property of the winery's productive means among all winegrowers
associated with the winery. Further, all costs, revenues and risks are split among members according to specific rules
drawn up independently by each CWS.

140 In its most simple version, the system groups a number of winegrowers who, by performing specific tasks in their
vineyards (aka plots) all year round, harvest a specific yield of wine grapes every year. The yield is then transported
to the winery, where the system's wine production is centralized and stored. The winery also sells the stored wine and
distributes the yearly profits among its associated winegrowers.

In this simple formulation two kinds of interactions can be distinguished: *interactions within activities* and *interactions*
145 *between activities*. The former represent the inter-dependency of the different components of the farm (vineyards and
buildings) that are spatially dispersed, whereas the latter represent the inter-dependency between the winegrowers and
the winery. Despite their names, both cases should be understood as flows of information from one entity (plot, farm,
winery) to another. Namely, when an explicit link between two material entities exists, the entities dispose of information
about their own state and each other's state. These interactions plus the shape of the CWS's network are illustrated in
150 figure 1

2.2 Data collection

We collected data from the Aude and Var administrative departments (southern France), both subject to major floods
that have impacted the winegrowing sector (Vinet, 2003; Bauduceau, 2001; Collombat, 2012; Chambre d'agriculture Var,
2014). Data were collected from several sources in order to identify common patterns and plausible hypotheses related
155 to CWSs.

The sources include qualitative interviews with winegrowers and heads of cooperative wineries (RETINA, 2014-2016) in
both departments, that provided useful insights into soil productivity, the stages of production, the behavior of the agents,

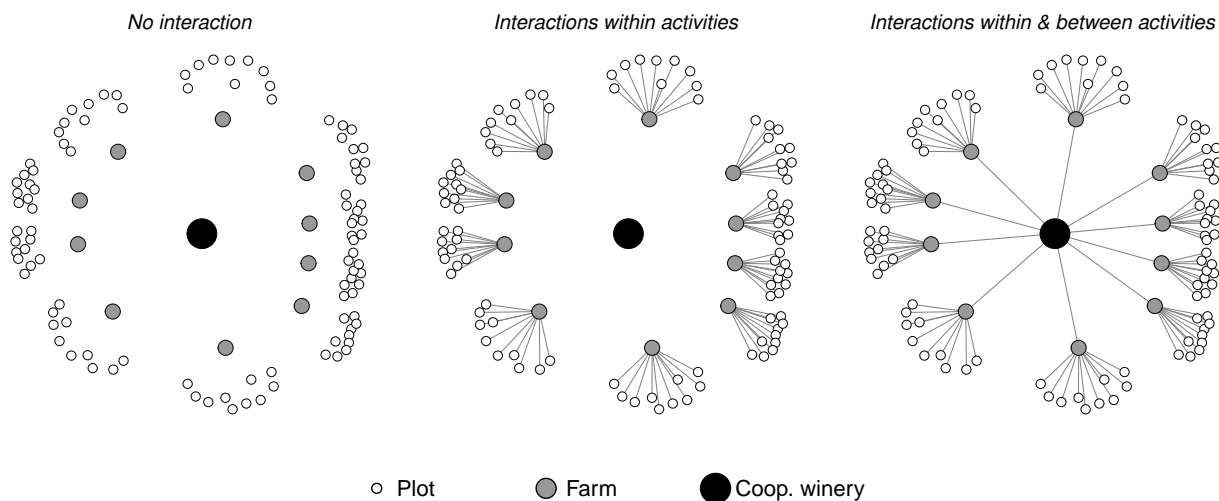


Figure 1. Shape of the kinds of interactions and network in the in the cooperative winemaking system

plausible business sizes and governing rules. On these subjects we also counted on the works of Biarnès and Touzard (2003); Chevet (2004); Agreste (2010); Battagliani et al. (2009) and FranceAgriMer (2012). The sequence of technical operations carried out by winegrowers is based on technical information provided by the Chamber of Agriculture.

Financial data and data related to price, costs and cost structures came from Folwell and Castaldi (2004); Centre d'économie rurale (2014, 2017); Chevet (2004); FADN (2014); INSEE (2016); CCMSA (2017); Brémond (2011) and FranceAgriMer (2012). Flood material damage was modeled using existing damage functions adjusted to the local context from Brémond (2011) and Rouchon et al. (2018). Lastly, patterns of exposure where obtained using geographical information from IGN (2020) and MTES (2020)

3 Model

The GOOPER model Table B1 in annex B further discloses these references and the main area(s) in which the information obtained has been relevant.



3 Method

170 3.1 Overview

The workflow of this paper is outlined in figure 2. To determine whether or not to take into account the existing interactions between material entities i



the simulations obtained from two experiments (subsection 3.1) carried out within the virtual laboratory provided by the COOPER model.

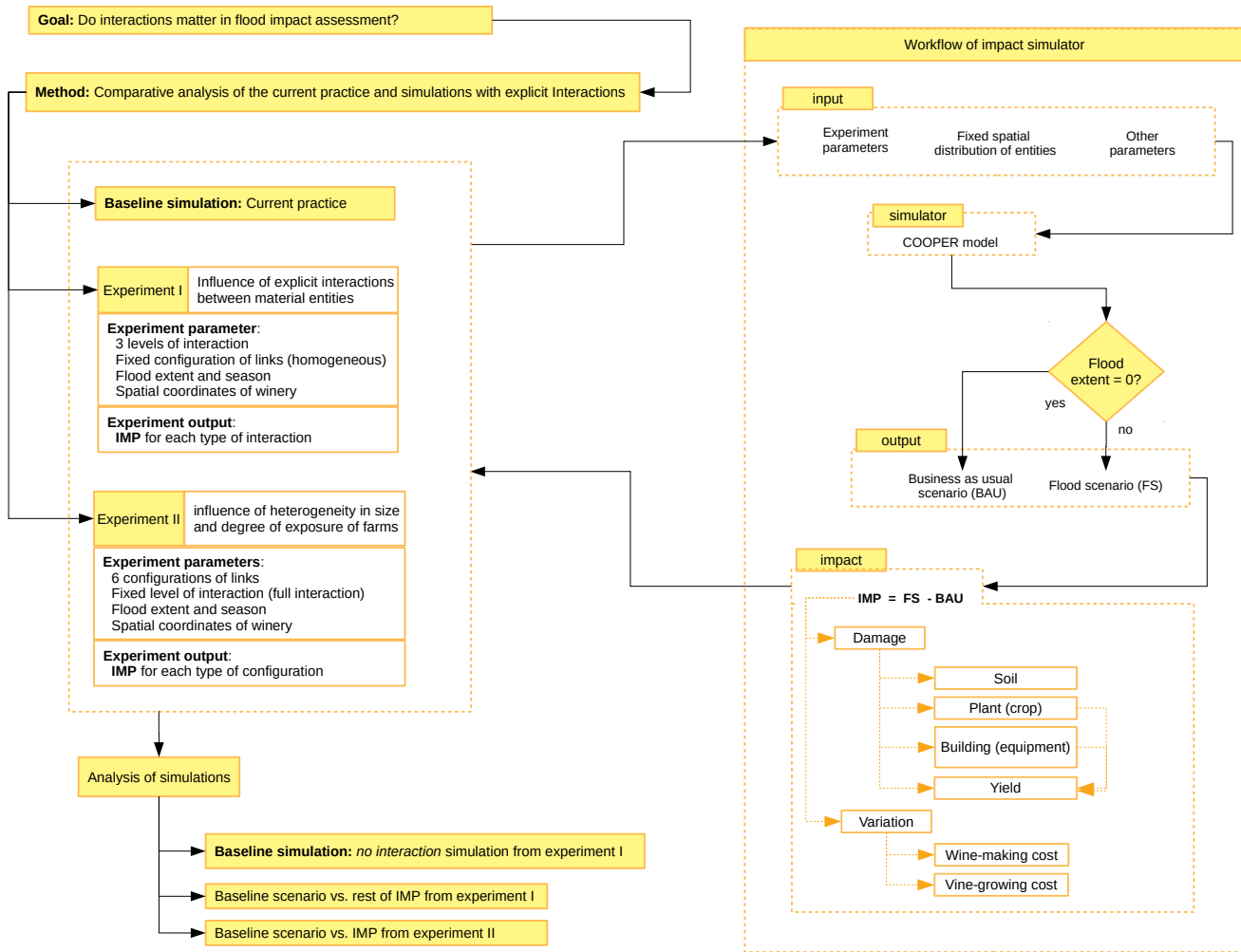


Figure 2. Workflow of the study



175 The COOPER model (Nortes Martinez et al., 2019) is an agent-based model we built as a virtual laboratory for the ex-ante estimation of impacts of a wide variety of flood phenomena over a CWS. ~~In this section, we present the main characteristics of the model and how we use it for the purpose of this article. For a more exhaustive disclosure, we refer the reader to the detailed description of the model available online at the~~ (subsection 3.2). Further additional details are



provided in the model documentation, available online at the CoMSES computational model library (Rollins et al., 2014).
180 computational model library (Rollins et al., 2014).

The first experiment (subsection 3.1.1) compares the estimate of flood impacts carried out following the usual practice (*no interaction*) with impact estimates made taking into account different degrees of interaction (the so-called *partial* and *full*). All these simulations are run on a fixed spatial distribution of material entities homogeneously linked to each other, making it possible to ensure that the source of variation is the presence of interactions. Furthermore, the experiment is
185 conducted in events of varying magnitude, so potential non-linearity can be evaluated.

The second experiment (subsection 3.1.1) builds upon the previous one, and compares the usual practice with estimates of impacts generated by linking the material entities in a heterogeneous way. In this experiment, only the greater degree of interaction (*full*) is considered.

The two experiments are carried out using two alternative locations of the winery building. The objective is to show the
190 effect of flooding or not of this central element of the system.

With the results obtained, we set up an index of differences. To build it, we start from the absolute damage obtained following the usual practice (subsection 4.1). Using this simulation as a baseline, we calculate the percentage that represents the difference in the series of estimated damages using the alternatives proposed in experiments I (section 4.2) and II (section 4.1).

195 **3.2 General overview Model**

The COOPER model is built ~~on~~ upon the description of the system provided in subsection 2.1. We modeled three types of material entities: farm land plots, farm buildings and the winery's building. These material entities are located in a virtual territory. At the same time, this territory is divided into cells that can host one and only one material entity.

Upon these three material entities we identify two kinds of agents: farms and winery. Each farm (understood as an
200 economic agent) is formed by the combination of a number of plots and a farm building in which all the farm equipment, stocks and harvested products are located. The winery (understood as an economic agent) is represented by only one building in which all equipment, stocks, products are assumed to be located. The material components of the winery are assumed to be one indistinct material component in one location, consequently any interactions *within activities* for the winery are not taken into account.

~~When a flood hits the system, it causes direct material damage to the material entities which may also disrupt the productive process in different ways that affect the economic agents.~~

3.3 Time and space representation

~~Each~~ In the COOPER model each time step represents one season. For both farm and winery, we count on simplified—and seasonally adjusted—versions of their own real-life complex schedules linked to biological cycles of vines. As a
210 result, the global internal schedule in the model is given by the coexistence and interaction of those individual schedules.

To illustrate the point, figure 3 outlines the global model schedule and each agent's own schedule. A year begins in winter and ends in autumn.

The material entities are located in a virtual territory that is divided into cells. Each cell can host only one material entity: either one farm plot, one farm building, or one winery building.

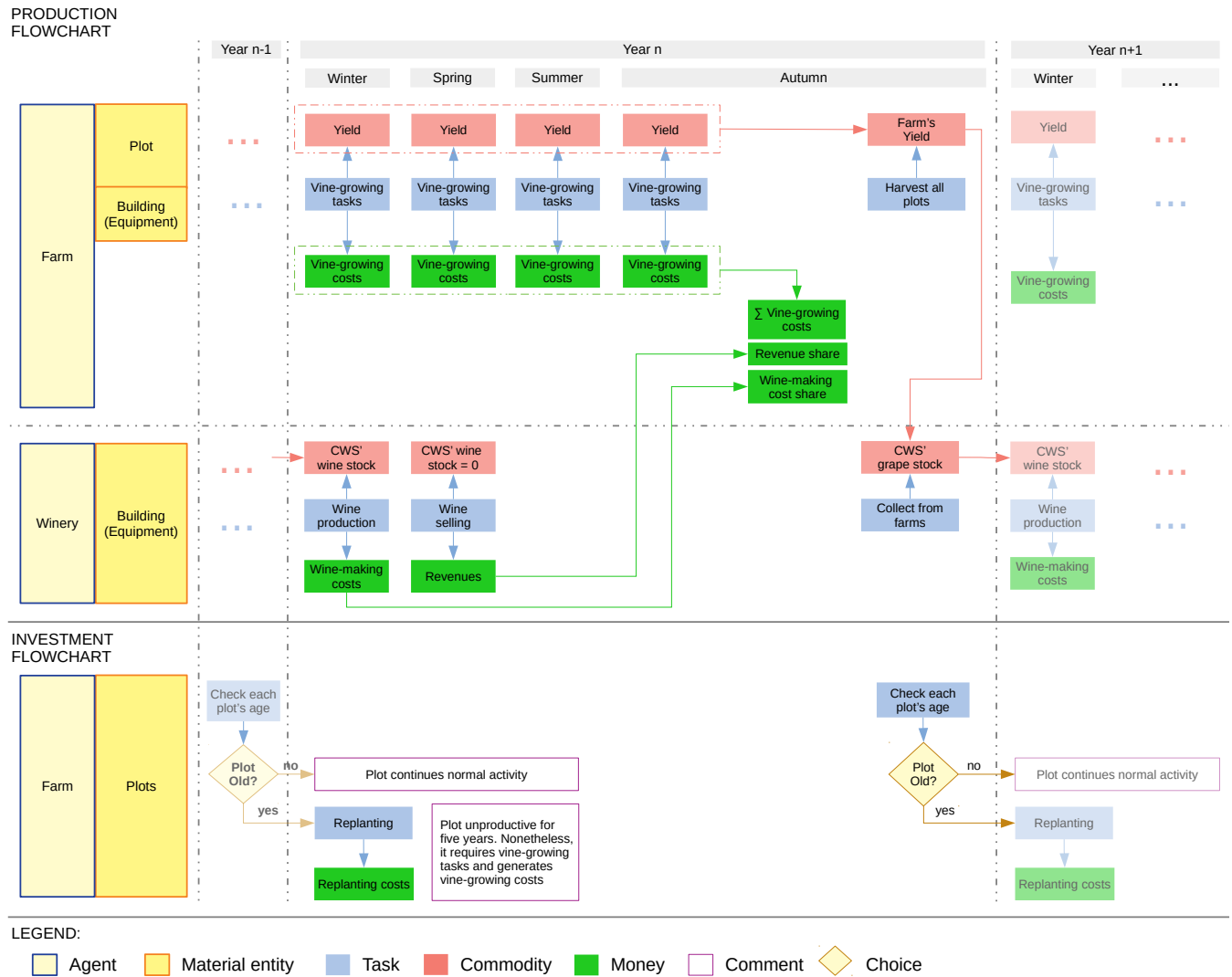


Figure 3. Production process overview and schedule



215 3.3 Production process I: Winegrowing process

The winegrowing tasks performed in the plots are organized on a seasonal schedule, starting in winter. Each farm covers its own winegrowing costs.

When their vines are too old (30 years), farmers replant their plots. Plots are unproductive for the first five years after replanting.

220 3.3 Production process II: Winemaking process

The winery also follows a seasonal schedule: in autumn it receives grapes from member farms. This input is transformed into wine in winter, and sold. production dynamic goes as follows: Farms perform tasks upon their plots which, on the one hand, enable each farm to obtain a yearly yield, and, on the other hand, provoke the apparition of vine-growing costs. These tasks take place during the four seasons. Each autumn, farms harvest their plots and move their yields to the cooperative winery. During the next winter, the cooperative produces wine with the yield obtained from the farms and commercializes the production in spring. The model assumes no stocks remain in summer. Each year, the winery shares the revenues from the sales minus the winemaking costs incurred, proportionally to the quantity of grapes provided by each farm. As there are both fixed and variable winemaking costs, the total cost of winemaking depends on the total input of grapes in a non-proportional relation. Once everything is sold (in spring), the cooperative winery splits both revenue and wine-making cost among farms proportionally to the yield they provided in the prior campaign (see mathematical annex). It is worth noting that there is a time gap between the transfer of the yields from the farmers to the winery and the transfer of revenues from the winery to the farmers. Therefore, there exists a time gap between the revenues the farmer is perceiving and the costs that they are effectively financing.

As it happens in real CWS, plots present heterogeneous ages. In the COOPER model, plots reaching 30 years old get replanted. The replanting takes place at the end of autumn and replanted plots rest unproductive for 5 years (20 time steps). Apart from the clear cost in terms of yield harvested during their first five years of life, replanting itself also bears monetary costs for farmers.

3.3 Flood process I: Intensity of a flood

3.2.1 Flood process: intensity and impacts of floods

240 Floods are defined by two parameters: extent and season of occurrence.

The territory. The virtual territory in which material entities are located is divided into two different areas: one subject to floods (flood-prone area), one not. In the COOPER model, floods are defined by two parameters: extent and season of occurrence. Flood extent is measured along the X axis in the interval $[0, 100]$ assuming the river is located in $X = 0 \forall Y$. So, for instance, a spring flood of extent 50 impacts all cells located in the band $[1-50]$ in the flood-prone area in spring.

245 In this study. In the study we are presenting here, only one flood can occur over the whole simulation period, thus a spring flood designates a flood occurring in the first spring after the beginning of the simulation.

3.3 Flood process II: Impacts of flood


250 ~~Floods can have simultaneous impacts on farm~~ When a flood hits the system, it causes direct material damage to the material entities –farm plots, farm buildings and ~~on the winery building.~~ They first cause material damage and then disrupt the activity compared to normal processes winery building– which may also disrupt the productive process in different ways, affecting the economic agents –farms and winery.

3.2.1 Material damage to farms plots and associated disruptions

255 ~~Material~~ At plot level, material damage is threefold: i) damage to the soil, considered independent of the season; ii) damage to yields, dependent on the season; and iii) damage to plants vines, stochastic and dependent on the season (destruction of the vines depends on a probability function, which is not the same all year long). ~~If the vines are destroyed, the plot will have to be replanted and the yield of that plot is lost~~ We consider necessary to distinguish winter from the ensemble of spring-summer-autumn and, within this ensemble, the case where vines are not destroyed from the case when vines are destroyed.

260 Winter is a special case. When plots are hit directly, the sole impacts that flood produce is soil-reconditioning. It provokes a direct financial impact over farms who own impacted plots (benefits will decrease as a consequence of the extra reconditioning cost), but not further damages over yield nor vines, therefore no reduction on production and on revenues will take place.

265 Concerning spring-summer-autumn, in the case that floods do not destroy the vines in the flooded plots, the harvest is lost in a variable amount linked to the season. Also, soil-reconditioning tasks should be performed. At farm level, the yield harvested will depend on the number of plots flooded. At the same time, plots whose yield is completely lost, save vine-growing cost to the farm. At winery level, as it happens at farm level, the yield collected will be affected by the number of plots hit owned by the winery's associates, and so will be the annual production and the sales. Ultimately the financial balances of the winery and the farms will reflect the impacts of the flood. ~~Destruction of~~

270 If vines are destroyed when plots are flooded, the consequences have further ramifications: at plot level, both the vines and the whole harvest is destroyed. At farm level, as in the ~~vines also changes both net income flows and investment flows (the plot has to be replanted).~~ This effect is measured by comparing the disrupted net income flow of the CWS over the whole duration of the simulation (30 years) with what would have occurred with no flooding. ~~prior case, you~~ lost depends on the number of plots flooded and vine-growing cost are saved. Vine destruction also introduces a longer term effect: destroyed plots need to be replanted. Assuming they are replanted immediately (next win  they will need 5 complete years to be considered productive. Therefore, *ceteris paribus*, the farm does not only loses the harvest of the current campaign but the harvest of the next 5 years by plot destroyed. At winery level, those longer term impacts will be reflected too.

3.2.2 Cost savings at farm level

280 ~~Savings in winegrowing costs are estimated in the plots in which the yield has been destroyed . Whether Vine growing~~
~~cost savings appear because, whether it is~~ due to the destruction of the vines or to direct damage to the yield, as soon as
the plot loses all its yield, the farm stops performing winegrowing tasks during the current campaign in the plot concerned
thereby saving the cost of the remaining tasks until the beginning of the following campaign.

3.2.3 **Material damage to the farm buildings**

285 ~~Material damage to farm building includes material damage to farm equipment. Damage to buildings is simplified in the~~
~~model and remains constant whatever the intensity of the flood. As for time spans, damages in soils, harvest and variations~~
~~in vine-growing costs are accounted to $t = 1$. If vines are not destroyed, variations in production, ergo in revenues and~~
~~wine-making costs, will be accounted to $t = 2$ (thus delayed one year); if vines are destroyed, impacts on production,~~
~~revenues and wine-making costs will last until $t = 7$ assuming plots are replanted in $t = 2$ (otherwise impacts will last~~
~~longer).~~

290 3.2.4 **Disruptions due to material damage to the farm buildings**

~~Buildings damaged by the flood have to be repaired. Until such repairs are carried out, the building cannot function~~
~~and~~ In addition to impacts on plots, farms can experience impacts that can be split into two kinds of consequences:
consequences due to buildings and materials flooded, and, once it happens, consequences due to the coping strategy
chosen. Farms are assumed to be motivated to preserve their *status quo ante*. It means, in absence of constraints,
295 buildings will be repaired and materials replaced right away, so the farm is fully operational next season². Same principle
applies to plot's replant: in the absence of constraints, it is done first winter season following the flood. But when the
~~winegrowing tasks cannot be carried out by the farm . The damage related to building is hit, we assume that part of the~~
~~loss of functionality depends on the farmer's coping tactics. vine-growing material is lost/hit. Farms, consequently, will~~
~~have to pay for reparations and, additionally, they cannot fully perform their seasonal tasks. To cope with the situation,~~
300 they can choose between two tactics:

3.2.5 **Farm coping tactics**

~~A farm can use two different coping tactics when its farm building is flooded: **Internal:** The flooding of the building~~
~~implies a disturbance that causes misperformance of winegrowing task. It results in both cost savings and yield losses. In~~
~~plots already partially damaged by the flood, the~~ The first one, hereafter labeled *external* tactic, states that farms whose
305 buildings are hit by a flood can hire external service providers to perform the task in its place. Such strategy saves all the
yield in plots since the tasks are fully performed, but increases the seasonal vine-growing costs. The alternative tactic,
henceforth referred as the *internal* tactic, establish that the farm counts on its own resources to perform the seasonal
tasks. Since part of the material is lost, we assume the farm can only perform the half of the tasks planned for the

²After the flood hits the farm in the beginning of the season, we assume that, in the absence of financial constraints, farms have enough time during the season to repair and be fully operational next one.

season. As a consequence, seasonal vine-growing cost decreases by 50% but there is an associated lost in yield losses
310 are added to those caused by the direct impact of the flood. **External:** To avoid a drop of performance, the farm pays for
external assistance to carry out the tasks, resulting in an increase in winegrowing costs but no additional yield losses.

3.2.6 Material damage to the winery building

Like the farm buildings, the winery building includes its contents: equipment and stocks of grapes or wine. It is assumed
that the winery stores grapes in its building in autumn, and stores wine from winter to spring. When a flood occurs, it
315 damages the building and completely destroys any stock present in the building at the time of the flood. The time span
for impacts derived from the choice of tactics is different: assuming the flood hits the system in year $t = 1$, effects over
vine-growing costs become part of impacts in $t = 1$, while effects over yield derived from the *internal* tactic will be felt in
year $t = 2$, once the yield is processed and the wine produced and sold. Both tactics eventually affect financial balances
but, while the *external* tactic limits impacts to the year in which flood hits the system, the *internal* tactic generates more
320 persistent impacts.

3.2.7 Disruptions due to damage to the winery building

Like disruptions in farms As it happens for farms, impacts over wineries have a twofold nature: first, regardless of the
season, when a cooperative winery is hit by a flood, the damaged winery building needs to be repaired. Until the repairs
model assumes damages in buildings and equipment. Second, these damages also affect the capacity of the winery to
325 perform its normal activities. Concretely, when the winery gets hit during winter, the material damage suffered impedes
the processing of the yield collected during the prior campaign, thus the wine production. With nothing to sell³, there are
no revenues for farmers and the wine-making cost is reduced to the winery's fixed costs⁴.

Insofar all production and sales are done in and through the cooperative winery, all the associated farms will lose
all production and revenues. They will be imputed, though, with their share of the winery's fixed cost and reparations.
330 Financial balances will reflect such situation.

If the winery is flooded in spring, we consider the wine-making processes already finished and the production ready to
be sold. However, material damages will make the winery lose the production and, as in winter, no revenues over the yield
of the prior campaign will be perceived. Contrary to winter, in spring, since wine-making activities are done, the building
cannot function and, depending on the season, grapes cannot be collected in the autumn, wine cannot be produced in
335 winter and sales cannot be made in spring. farms will be imputed with all the wine-making cost corresponding to its share
plus the reparations needed.

3.2.8 Cost savings at winery level

³Since floods happen at the beginning of the season, the winery will have time to be fully functional for the next season, and to perform sales.
However, to not be able to produce the wine, has left it with no production to be sold.

⁴Winemaking costs are twofold: fixed and variable.

Winemaking costs are twofold: fixed and variable. Fixed winemaking costs are never saved, whereas variable winemaking costs are saved depending on the season in which the flood occurs. It During summer season, wineries are not expected to perform any essential task. Therefore, when they are flooded, impacts are limited to reparations, with no further effect besides the ones over the financial balance of the winery and its associated farms.

Floods over the winery's buildings in autumn, hinders the winery from collecting the yield coming from its associated farms. Under such circumstances, all farms lose their yields. This fact prevents the system from having input to produce wine during winter of the following campaign. Without production, effects are the same as the already described situation for winter, but delayed by one period: no sales, ergo no revenues, and wine-making cost reduced to the fixed cost.

Concerning the imputation of costs from the winery to its associated farmers, we can differentiate two different mechanisms: the first one is when the winery is flooded, but production can be done or has been done. In such case, reparation costs are imputed among associated farms proportionally to the yield provided by each farm (see mathematical annex). In such regard, it is worth noting that, inasmuch as fixed costs exist in the structure of winemaking costs and the way these costs are shared among the farms costs of the winery, cost-revenue sharing rules create an implicit interaction among all the farms in the CWS: if one farm loses its whole harvest, it will not receive any revenue from the winery, but neither will it have to pay its "normal" share of fixed costs. All other farms will consequently be indirectly impacted because they will now have to pay that share of fixed costs.

3.2.9 Impact calculation

Impacts are calculated by comparing a Business as Usual Scenario (BAU) with a concrete Flood Scenario (FS). The second mechanism is triggered only when the production-commercialization process gets disrupted, and production cannot be done. In this case, wine-making cost is reduced to the winery's fixed cost. Added to reparation costs, both are imputed proportionally to the number of farmers (see mathematical annex). In other words, the total

3.2.10 Flood impact calculation

In the COOPER model, the CWS rests, both at collective and individual levels, over a vector of five key variables: production $—Q_t—$, revenues $—R_t—$, costs $—C_{vg}$ (vine-growing) and C_{wm} (wine-making)— as well as investments and reinvestments $—I_t$. This last variable (I_t) serves us to group all reparations to be done in the system after a flood, reinvestments in vines and materials and, also, planned investments independent of the flood.

Every time a material entity in the CWS is flooded, one or more of those variables are going to experience a change. Thus, assuming that BAU_t and FS_t are two vectors of key variables for their respective business as usual scenario (BAU) and flooding scenario (FS):

$$\underline{BAU}_t = (I_t, Q_t, R_t, C_{vgt}, C_{wm_t}) \quad (1)$$

$$\underline{FS}_t = (I'_t, Q'_t, R'_t, C'_{vgt}, C'_{wm_t}) \quad (2)$$

370 ~~We can define the impact of a concrete flood is the sum of the differences between the expected flow of inputs and outputs of the productive process in the absence of flood (BAU) and the actual flow of inputs and outputs for each simulation period.~~

4 ~~Simulation protocol and experiments~~

flood at any moment t as:

$$\underline{Imp}_t = \underline{FS}_t - \underline{BAU}_t \quad (3)$$

375 In the COOPER model, information on those five key variables is recovered through a collection of 10 different indicators (see table 1). These indicators are available for every individual farm in the CWS at any time step. Insofar as the collectivity –the CWS– in the COOPER model is the result of the aggregation of the individuals –the farms– rather than an extrapolation, the same 10 indicators (thus the five key variables) available at the farm level are also available for the CWS as a whole by means of the aggregation of the individual values.

380 Impacts issued from the COOPER model can accommodate the different impact classifications existing in the literature insofar as both temporal and spatial scales are present in the model and impacts can be tracked down throughout the system. Damage classifications within the CWS are, nonetheless, agent-dependent, thus, depending whether we chose farms or the winery or, even, a particular farm i , we will classify the same damages with different labels. In the work we are presenting here, given that we are studying the CWS as a whole and as an encapsulated system (not in interaction
 385 with any other), we do not need to adscribe to any classification.

3.1 Simulation protocol and experiments

~~We designed a general setup that remained fixed across simulations, and~~ To answer to our question, we performed a twofold experiment designed to analyze the ~~extent of divergence between estimating impacts~~ divergence of estimated flood impacts, simulated with the COOPER model ~~and current practices of damage assessment at local levels, according~~
 390 to different schemes of interactions between economic entities.

3.2 ~~General setup across simulations~~

Regardless of the interaction scheme used for each particular experiment, all simulations share the same configuration to avoid sources of unwanted variation. This general setup presents the following characteristics across simulations.

<u>Key variable</u>	<u>Indicator</u>	<u>Agent</u>
I_t	<u>Damages in soils</u>	Farm
I_t	<u>Damages in plants</u>	Farm
Q_t	<u>Damages in harvest due to floods</u>	Farm
Q_t	<u>Damages in harvest due to plant destruction</u>	Farm
C_{vg}	<u>Variations in vine-growing cost</u>	Farm
Q_t	<u>Damages in harvest due to damages in farm</u>	Farm
I_t	<u>Damages in farm's equipment</u>	Farm
C_{wm}	<u>Variations in wine-making cost</u>	Winery
I_t	<u>Damages in winery's equipment</u>	Winery
Q_t	<u>Damages in harvest due to damages in winery</u>	Winery

Remark: Each indicator includes on the left side of its frame the variable to which it refers, according to the nomenclature included at the beginning of this section: I_t = Investment | Q_t = Production | R_t = Revenues | C_{vg} = Vine-growing cost | C_{wm} = Wine-making cost

Table 1. Indicators



All the simulations presented in this article shared the following characteristics:-

395 3.1.1 **Simulation time span**

30 years-

3.1.2 **Material entities**

400 ~~The CWS~~ The CWS used for simulations in our two experiments is composed of :~~One winery building (thus 1 51 agents and 551 material entities: One winery agent)-~~with a winery building; 50 farm buildings (thus 50 farm agent)-agents each with a farm building,, and sharing a total of 500 plots ~~-The size of each plot is assumed to be of size 1 ha. The CWS thus mobilizes 500 ha of productive land.~~

3.1.3 **Spatial distribution**

Spatial location is a key factor in the assessment of flood impacts and how far they spread through the system. To avoid noise from variations in the location in our simulations, the physical location of all material components belonging to farms

405 ~~(Farm buildings and plots) is the same in all the simulations. This insures that the material remain in the same location for each simulation. This ensures that the physical~~ components of the farms are always impacted in the same way by a flood of a given extent and ~~in-at~~ a given season (see Table 2). Concretely, 20% of the farm buildings (i.e. 10 out of 50) are located in the flood-prone area, randomly distributed within the band [30–100] (see Figure 4), whereas 30% of the plots (i.e. 150 out of 500) are in the flood-prone area, randomly distributed within the band [10–100] (see Figure 4).

410 Concerning the location of the winery building, we performed two sets of analysis: one with the winery building located at position 1 in the flood prone area (and consequently always flooded), one with the winery building located outside the flood prone area (and consequently never flooded). ~~Regarding farm buildings, 10 of them (20% of farm buildings) are located in the flood-prone area, randomly distributed within the band 30–100(see Figure 4). 150 plots (30% of 500) are also within the flood-prone area, randomly distributed within the band 10–100(see Figure 4).~~

415 3.1.4 Other parameters

~~A complete list of initialization values and endowments is available in the COOPER description in the CoMSES computational model library~~Productive activities in the CWS are simulated for time spans of 30 years, divided in 4 seasons.

3.2 Experiment I: Influence of the presence of explicit links between material entities

3.1.1 Experiment I: Influence of the presence of explicit links between material entities

420 3.1.2 Goal

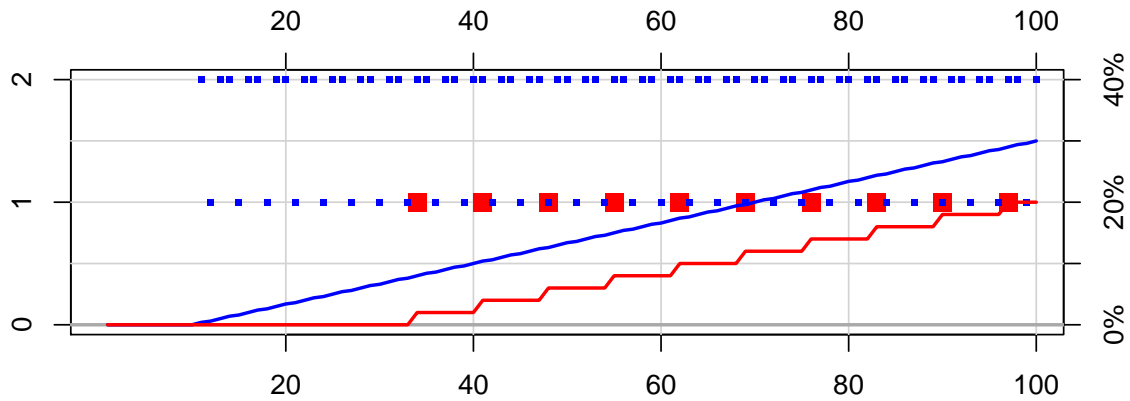
~~Protocol to compare~~Our first experiment targets methods of flood damage estimation and the influence that they have on the resulting impact.

3.1.3 Configurations of links

425 ~~This experiment uses our so-called *homogeneous* configuration: all the farms are the same size (10 plots) and the same proportion of plots are located in the flood-prone area (around 30%). See table 4 for more information.~~

Table 2. Common characteristics for the location of material components in the simulations

Element	Number of elements in		Total
	Flood area	Safe area	
Winery	0 or 1	0 or 1	1
Farm	10	40	50
Plot	150	350	500



Legend: blue represents plots, red farm buildings. The x-axis indicates the extent of the flood. The left y-axis gives the number of elements located at the position of the corresponding points. The right y-axis shows the corresponding cumulative percentage given by the lines. For example, 10% of the plots (blue lines) are located in the floodplain at a position of 40 or under, 2 plots are present at this precise position.

Figure 4. Spatial distribution of farms buildings and plots inside the flood-prone area

3.1.4 Description

To Concretely we search to estimate the influence that the inclusion of explicit interactions between material entities has on the estimation of flood damage. To do so, we sequentially simulate and compare three alternative cases (figure 1): There are. First, the no interaction case, which corresponds to current practices in damage assessment, and includes no explicit links between material entities, thus no explicit interaction exists and each entity only has access to its own state. This corresponds to current practices of damage assessment. The damage is assessed including within interactions. Therefore, whereas farmers Next, the partial interaction case, in which only interactions within activities are explicitly included. Namely, farms and plots have access to both their own states and each other's states, whereas the winery only has access to its own state. This case Last, the full interaction case, which accounts for interactions both within and between within and between activities. Accordingly, all material entities in the system have access to their own states and each other's states.

3.1.5 Additional hypotheses linked to the experiment

As in two of the cases, the In both no interaction and partial interaction cases, due to the lack of explicit links, information on other entities' states does not flow throughout the system; several additional hypotheses are required concerning. In these two cases, additional assumptions are required to perform damage estimation and business disruptions.

In the case of The first one, referred as A1, is an implicit assumption in current practices of damage assessment and concerns only the *no interaction* ; winegrowing tasks can all be accomplished in non-flooded plots at the normal cost, as if the buildings of the corresponding farms had not been flooded. Under assumption A1 case. It can be stated as "Independently of whether farm buildings have been flooded, winegrowing tasks can all be accomplished in non-flooded plots at the normal cost, as if the buildings of the corresponding farms had not been flooded". In other words, under assumption A1, grape production depends only on what happens in the plots ; i.e. (damage to plots and damage to the farm buildings is estimated separately at farm level. This is an implicit assumption in current practices of damage assessment. This is different to what happens in the case of *full interaction* case, where whether the tasks required in the plots are performed or not depends on the state of the farm building (flooded/not flooded) and the coping tactic used by the farm concerned).

Additionally, for The second and third assumptions concern both the *no interaction* and *partial interaction* cases ; we make the two following hypotheses:-

A2 The winery receives the quantity of grapes computed as if no farm buildings or plots were flooded.-

A3 The cost of wine production is computed as if no farm buildings or plots were flooded.-

Once again, both assumptions are part and are still part of current practices of the current practices in flood damage assessment. Under these The first of them, referred as A2, states that *the winery receives the quantity of grapes computed as if no farm buildings or plots were flooded*, whereas the second one (referred as A3) specifies that "The cost of wine production is computed as if no farm buildings or plots were flooded." Under these two last assumptions, wine production and sales depend only on what happens to the winery building, while damage to plots and farms buildings can be estimated separately at farm level. This is different to the dynamics in the *full interaction* case, where the quantity of grapes the winery receives depends on the effective damage to the farm, which also makes it possible to calculate the loss of wine products and impacts on winemaking costs.-

Table 3 sums up which hypothesis applies to each case.

A complete list of initialization values and endowments is available in the COOPER description in the CoMSES computational model library.

3.1.6 Simulations

Table 3. Modalities of interactions and assumptions for damage estimation

Case	Assumptions
<i>No interaction</i>	A1 + A2 + A3
<i>Partial interaction</i>	A2 + A3
<i>Full interaction</i>	—

470 Simulations are run for flood extents from 15 to 100 — increasing at a step of 5 — for each combination of farms' coping tactic, location of the winery, season and type of interaction. As the GOOPER model includes stochastic processes, each flood scenario is replicated 50 times. This experimental design gives a total of 43 200 different simulations. In contrast, in the *full interaction* case, where all links are explicit, there is no need for those assumptions. Regarding hypothesis **A1**, in the *full interaction* case, whether the tasks required in the plots are performed or not depends on the state of the farm building (flooded / not flooded) and the coping tactic used by the farm concerned. Regarding hypotheses **A2** and **A3**, in the *full interaction* case, the quantity of grapes the winery receives depends on the effective damage to the farm, which also makes it possible to calculate the loss of wine products and impacts on winemaking costs.

475 For this experiment, we complete the general setup mentioned above with the following configuration: all the farms are the same size (10 plots) and the same proportion of plots are located in the flood-prone area (around 30%). This configuration is labeled *homogeneous* configuration (See table 4 for more information).

3.1.7 Results

480 The average impact resulting from each simulation is The results of experiment I are presented in section 4.2 as a comparison of the estimated impacts using the *no interaction* case (standard practice) as baseline.

3.2 Experiment II: Influence of agent heterogeneity in flood damage estimation

3.1.1 Experiment II: Influence of agent heterogeneity in flood damage estimation

3.1.2 Goal

485 Protocol This experiment is designed to test whether heterogeneity in factors such as farm size or farm size and degree of exposure of farms has an impact on the amount of damage suffered by the system in the case of flooding.

3.1.3 Configurations of links

490 Several To introduce these two factors of heterogeneity without modifying the spatial distribution of material entities, we construct different configurations of links between material entities were simulated plots and farms' buildings by modifying which plots belongs to which farm. These configurations are as follows (see figure 5 for a schematic representation and table 4 for the main characteristics of the spatial distribution of the different configurations):

homogeneous (figure 5a) All farms have the same number of plots (10). The proportion of plots in the flood-prone area is the same in all farms.

size (figure 5b) 10 farms are big (30 plots), 40 farms are small (5 plots). The proportion of plots in the flood-prone area is equivalent for each farm.

495 **exposure-worst** (figure 5c) All the farms have the same number of plots. The farms whose building is located in the flood-prone area have all their plots located outside the flood-prone area. The plots in the flood-prone area are approximately equally distributed among the remaining farms.

exposure-best (figure 5d) All the farms have the same number of plots. The farms whose building is located in the flood-prone area also have all their plots located in the flood-prone area. The remaining plots in the flood-prone area are approximately equally distributed among the remaining farms.

size-exposure-worst (figure 5e) 10 farms are big (30 plots), 40 farms are small (5 plots). All big farms' buildings are located in the flood-prone area whereas all their plots are located outside the flood-prone area. All the plots in the flood-prone area thus belong to small farms, whose buildings are located outside the flood-prone area.

size-exposure-best (figure 5f) 10 farms are big (30 plots), 40 farms are small (5 plots). The building and all the plots belonging to 10 of the small farms are located inside in the flood-prone area. The remaining plots located in the flood-prone area belong to the remaining small farms. The plots and buildings of the 10 big farms are located outside the flood-prone area.

3.1.4 Description

~~The location of material entities is fixed, we vary links between them by introducing two factors of heterogeneity (size and individual exposure) of the agent 'farm'. By making case of *no-interaction* of the prior protocol the baseline (current damage assessment) we can compare the extent to which the impacts calculated with the aforementioned configurations of links diverge.~~

~~In the case of fixed distribution of material entities over the terrain, we vary links between them by introducing two factors of heterogeneity (size and individual exposure) of the agent 'farm'.~~

3.1.5 Additional hypotheses linked to the experiment

~~The experiment used both the *no-interaction* and the *full-interaction* cases from the prior experiment as baseline and actual scenarios respectively.~~

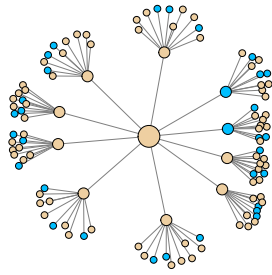
3.1.6 Simulations

~~Using the *full-interaction* modality, simulations were run for flood extents ranging from 15 to 100 — increasing at a step of 5 — for each combination of farm coping tactic, season and configuration of links. As the GOOPER model includes stochastic processes, each flood scenario is replicated 50 times. This experimental design gives a total of 86 400 different simulations.~~

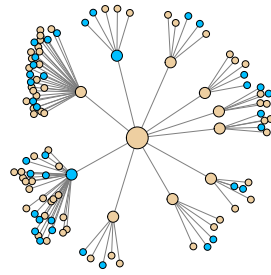
3.1.7 Results

525 ~~The average impact resulting from the simulations is presented~~ We simulate the damage in the *full interaction case* for each of these configurations and compare them to the same baseline as in the experiment I (*no interaction and homogeneous*⁵). The results are analyzed in section 4.1.

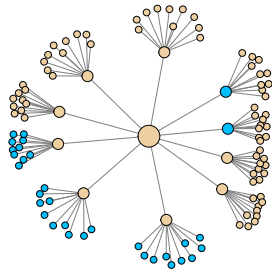
⁵When damage are assessed in the *no interaction* case, there is no influence of the configuration of links, because of hypothesis **A1**.



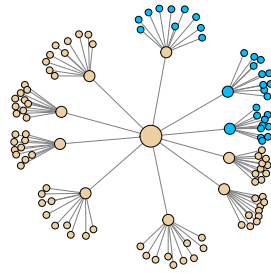
(a): Homogeneous farm size and plot exposure



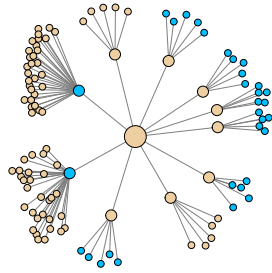
(b): Heterogeneous farm size and homogeneous plot exposure



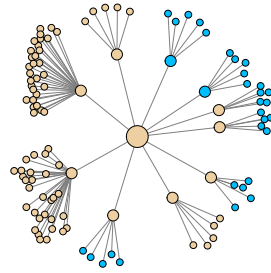
(c): Heterogeneous plot exposure. Worst case: maximizing indirect damage



(d): Heterogeneous plot exposure. Best case: minimizing indirect damage



(e): Heterogeneous plot exposure and farm size. Worst case: maximizing indirect damage



(f): Heterogeneous plot exposure and farm size. Best case: minimizing indirect damage

Location: ● Prone area ● Safe area

Entity: ○ Plot ○ Farm ○ Coop. winery

Figure 5. Schematic representations of the configurations of links allowing us to introduce two sources of agent heterogeneity: farm size and flood exposure

Table 4. Comparison of the main spatial distribution characteristics of the different configurations of links

configuration	size	exposure	n_{farms}	building	n_{plots}	exposed plots
<i>homogeneous</i>	homogeneous	homogeneous	10	exposed	10	32%
			40	safe	10	30%
<i>exposure-best</i>	homogeneous	heterogeneous	10	exposed	10	100%
			40	safe	10	12%
<i>exposure-worst</i>	homogeneous	heterogeneous	10	exposed	10	0%
			40	safe	10	38%
<i>size</i>	heterogeneous	homogeneous	8	exposed	5	38%
			32	safe	5	32%
			2	exposed	30	33%
			8	safe	30	28%
<i>size-exposure-worst</i>	heterogeneous	heterogeneous	0	exposed	5	–
			40	safe	5	76%
			10	exposed	30	–
			0	safe	30	–
<i>size-exposure-best</i>	heterogeneous	heterogeneous	10	exposed	5	100%
			30	safe	5	66%
			0	exposed	30	–
			10	safe	30	0%

Remark: the first column gives the name of the configuration, the column "size" (respectively "exposure") indicates whether this configuration is considered as homogeneous or heterogeneous in terms of size of farms (respectively in terms of proportion of plots exposed to flood). The following columns give quantitative information. For the corresponding configuration, there is n_{farms} farms that have their building in the situation given by the column "building", each connected to n_{plot} plots. The proportion of exposed plots belonging to these farms is given in the column "exposed plots".

3.1.8 Simulations performed

530 For both experiments, simulations are run for flood extents from 15 to 100 – increasing at a step of 5 – for each combination of farms' coping tactic, and season. As the COOPER model includes stochastic processes, each flood scenario is replicated 50 times.

For experiment I, the combinations are completed with each case for the location of the winery and the type of interaction. For experiment II, the combinations are completed with each case of configuration of links.

These experimental designs result in a total of 43 200 different simulations for experiment I and 86 400 different simulations for experiment II.

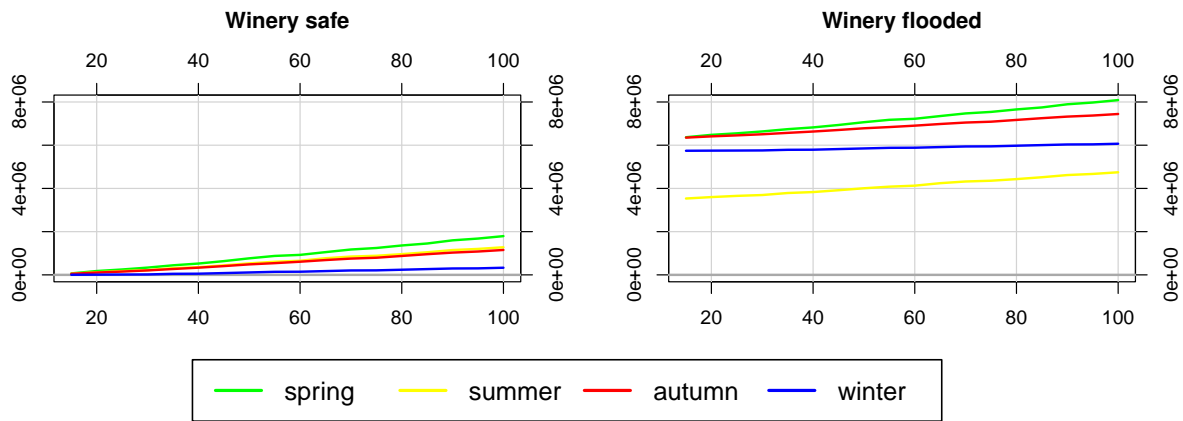
535 4 **Influence of interactions on damage estimation**Results

4.1 **Baseline**

Figure 6 shows the absolute flood damage for the CWS according to the current practice. The extent of the damage depends mainly on whether the winery was flooded or not, due to the importance of the equipment in the cellar. The damage also differs greatly depending on the season of the flooding. The damage increases in proportion to the flood extent, which reflects the increase in the number of flooded material entities.

540 For the system considered, the potential added value per year is 794,000 euros. This level of annual activity would be achieved if all plots were productive in the same year (which never happens, due to replanting of old plots). The damage represents up to 10 times the annual activity of the system when the winery is flooded, 13 times when it is not.





Remark: In each figure, the x-axis indicates the extent of the flood; the y-axis corresponds to the absolute damage in euros.

Figure 6. [Absolute damage for the baseline simulation](#)

4.2 [Influence of interactions on damage estimation](#)

545 In this section, we analyze the importance of accounting for interactions between the entities of a CWS in estimating
 flood damage. The results are shown in Figure 7. In the figure, the different lines show the relative difference in damage
 between cases of *partial interaction* (dashed lines) or *full interaction* (solid lines) and of *no interaction*, considered as the
 baseline. The results are split into sub-figures to show the effect of the season in which the flood takes place and of the
 farm coping tactic. The red lines correspond to the case in which the winery building is flooded, and the blue lines to the
 550 case in which it is not flooded (safe).

4.3 **Qualitative analysis**

4.2.1 [Qualitative analysis](#)

Figure 7 shows two types of implications of the assumptions A1 to A3. The first type of implication results from the fact
 that, when all interactions are not taken into consideration, the extent of some indirect damage cannot be captured,
 555 leading to underestimation of damage in cases with *no interaction* and *partial interaction* compared to the case with *full
 interaction*. When the winery building is safe, this applies in all seasons: the blue solid lines (*full interaction*) are always
 above the blue dashed lines (*partial interaction*), which are above 0 (*no interaction*). When the winery is flooded, the
 aforementioned underestimation also applies in all seasons except autumn: the red solid lines are always above the red
 dashed lines, which are above 0, except in autumn where the red solid lines are below 0.

560 The second type of implication occurs in autumn, when assumption A2 leads to some double counting, and hence to overestimation of damage in the cases of *no interaction* and *partial interaction* compared to the case with *full interaction*. Wine production depends on the yield of grapes supplied by the farms, and hence on the grape losses incurred by the farms. Under assumption A2, (*partial interaction* and *no interaction*), wine production in the cooperative winery in autumn is independent of the losses incurred by the farms. Thus, under assumption A2, the part of the harvest that is lost to
565 the farms is also considered lost to the cooperative winery. The bigger the flood, the bigger the losses to the farms, the more the double counting. In other seasons, no such double counting occurs because the quantity of grapes in the winery building does not depend on the quantities currently present on the farms. For instance, in winter, wine production in the winery building depends on the grapes harvested in autumn, not on the grapes currently growing in plots that will be harvested the following season.

570 Coming back to our explanation for underestimation of damage in the other cases, whether or not the winery building is flooded has no impact on the sign of the differences, even if the magnitude is much greater when the winery building is not flooded. This difference in magnitude originates from the fact that material damage is much greater when the winery building is damaged, and the relative difference is consequently lower.

In spring and in summer, there are differences between the cases of *partial interaction* and *no interaction* but the
575 differences are smaller than between the cases of *full interaction* and *partial interaction*. It is assumption A3 that leads to the following statement: In cases of *partial interaction* and *no interaction*, the costs of winemaking in the year following the flood are overestimated insofar grape losses at the farms level are not taken into account in the cost estimation. This also happens in autumn.

In winter, there are no losses of grape yields in flooded plots. Grape losses in this season only occur to farms that
580 apply the internal tactic when their building is flooded insofar such tactic provokes further yield damage due to task misperformance. Observable differences are explained by assumption A1, which is also the reason why the differences begin at flood extent 30 (first building impacted). The fact that the difference between cases of *partial interaction* and *no interaction* is noticeable in winter is related to the importance of the seasonal tasks performed in terms of loss of yield. This is also the case in autumn, but not in spring and summer. In spring and summer, the tasks are less important with
585 respect to the future yield, and the plots are also more vulnerable: grape yield losses are more directly linked to flooding of plots than to flooding of the farm building. In the case of the external tactic, it is also assumption A1 that explains the difference, but the impact is not loss of the grape yield, but increments in winegrowing costs. In Figure 7, this increment is important only in winter. In this case (external tactic, winter), in Figure 7, the curves for *partial interaction* and *full interaction* match perfectly.

590 4.3 Quantitative analysis

4.2.1 Quantitative analysis

First, when the winery building is flooded, the differences increase with the extent of the floods, but remain negligible, except in autumn. This because the material damage to the winery building is very severe. In autumn, double damage accounting leads to a difference of between 10% and 20%, increasing linearly with the number of plots flooded, and
595 hence with the extent of the floods (because of the spatial configuration chosen, see Figure 4).

When the winery building is not flooded, in spring, summer, and autumn, the differences are about 10%, increasing to 20% in autumn for the internal tactic when the farm building is flooded. In winter, the differences are negligible as long as no farm building is flooded. Otherwise it is about 20% for the external tactic and 40% for the internal tactic.

It is important to note that in spring and summer, the differences between *partial interaction* and *full interaction* are
600 bigger than between *no interaction* and *partial interaction*, independently of the chosen tactic. This is also the case in autumn, but only for the external tactic. This means that in these cases, it is more important to clarify the links between economic entities (farms and the winery) than within economic entities (plots and the farm building). In winter, for both tactics, and in autumn for the internal tactic, there is a clear difference between the three cases. The gap between the *no interaction* and *partial interaction* is bigger than the gap between the *partial interaction* and full interaction. Consequently,
605 in these cases, it is more important to establish the links within economic entities (between material components) than between economic entities. Finally, as floods can occur in any season, it is impossible to draw final conclusions about which type of interactions it is most important to take into consideration. Both should to be taken into account.

5 Influence of configurations of interactions in damage estimation

4.1 Influence of configurations of interactions in damage estimation

610 The analyses presented in section 4.2 apply to a particular configuration of interactions. All the farms own exactly 10 plots (homogeneous size) and have more or less the same ratio of plots located in the flood prone area (homogeneous exposure). In the case of *no interaction*, it is not important to know exactly which farm the plots belong to: as explained previously, in this case, when assessing damage, it is assumed that the farm to which a plot belongs is not flooded. This is not the case for *partial interaction*, or for *full interaction*. In these cases, even if all the material components are located
615 at exactly the same place, the way they are linked may have an influence on flood damage. In this section, we analyze this influence.

In section 4.2 we also showed that interactions have the most influence when the cooperative winery is not flooded, so in this section, we detail the case when the cooperative winery is not flooded (Figure 8). However, in the spirit of full disclosure, we also briefly analyze the case when the cooperative winery is flooded with no additional figures. In
620 this case, the relative differences between the configurations are very similar. In fact, the main damage originates in the cooperative winery, and any difference originating from farm heterogeneity is offset at the level of the cooperative winery.

This has direct implications for the significance of the double counting bias mentioned in the previous section: it is almost independent of farm heterogeneity (about 12% in the case of *no interaction*). This is also true for other seasons for which the damage propagation bias is negative, but almost negligible (1 – 2% in spring, 1 – 3% in summer, 0 – 2% in winter).

625 4.2 Qualitative analysis

4.1.1 Qualitative analysis

When the cooperative winery is not flooded, Figure 8 shows the relative differences in damage at the system level between the simulations of configurations presented in Table 4 for the case of *full interaction*, compared to the case of *no interaction*.

630 First, it can be seen that in all seasons, there is always less damage in the case of *no interaction* than in the case of the *full interaction*, for all configurations of links. The same bias as in section 4.2 is observed in spring, summer and autumn: there is a positive difference of about 10% between simulations with *full interactions* and simulations with *no interactions*. Differences between the configurations of links appear when the first farm building is flooded (flood of extent 30) and become more visible in parallel with the increase in flooded buildings.

635 The *size* configuration (green line), which represents big farms and small farms with comparable exposure, does not introduce a major difference from the *homogeneous* configuration (black lines) in which all farms are the same size with equivalent exposure. This is also true for the two configurations that introduce heterogeneity in terms of exposure: *exposure-best* (solid blue lines) and *exposure-worst* (dashed blue lines).

Clear differences only appear when both types of heterogeneity are introduced and combined. In this case, the configuration that suffers the most damage is always the *size-exposure-worst* one (dashed red lines). In this configuration, all 640 the buildings belonging to the big farms are located in the flood-prone area, but their plots are located outside. When their building is flooded, all the tasks required for their production are disrupted, which results either in extra costs (external tactic) or extra yield losses (internal tactic). This is the worst configuration for such effects. The configuration that suffers the least damage is always the *size-exposure-best* one (solid red lines). In this configuration, all the big farms are located 645 outside the flood-prone area. Thus, the buildings located in the flood-prone area belong to the small farms, and potential disruption of tasks only concerns a few plots. As these plots are located in the flood-prone area and suffer direct damage from the flood, the disruption of tasks is not that important. These differences are particularly clear in winter when many of the tasks on plots have to be completed under both tactics, and in autumn under the internal tactic, when being unable to harvest involves high yield losses.

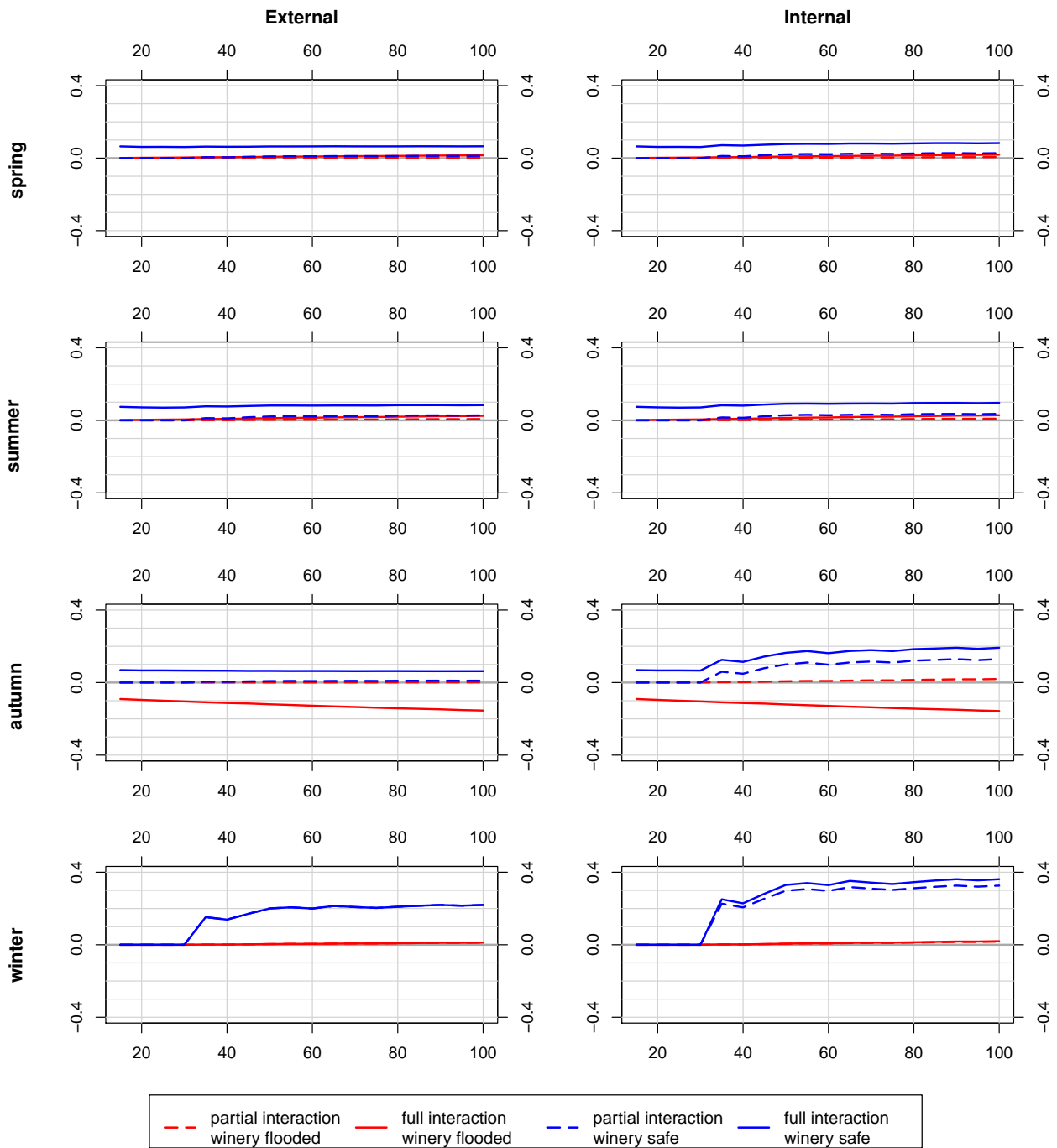
650 4.2 Quantitative analysis

4.1.1 Quantitative analysis

Concerning the magnitude of the differences between configurations, relative differences may be quite important. Under the configuration that suffers the most damage (*size-exposure-worst*), relative differences may be close to 110% in winter,

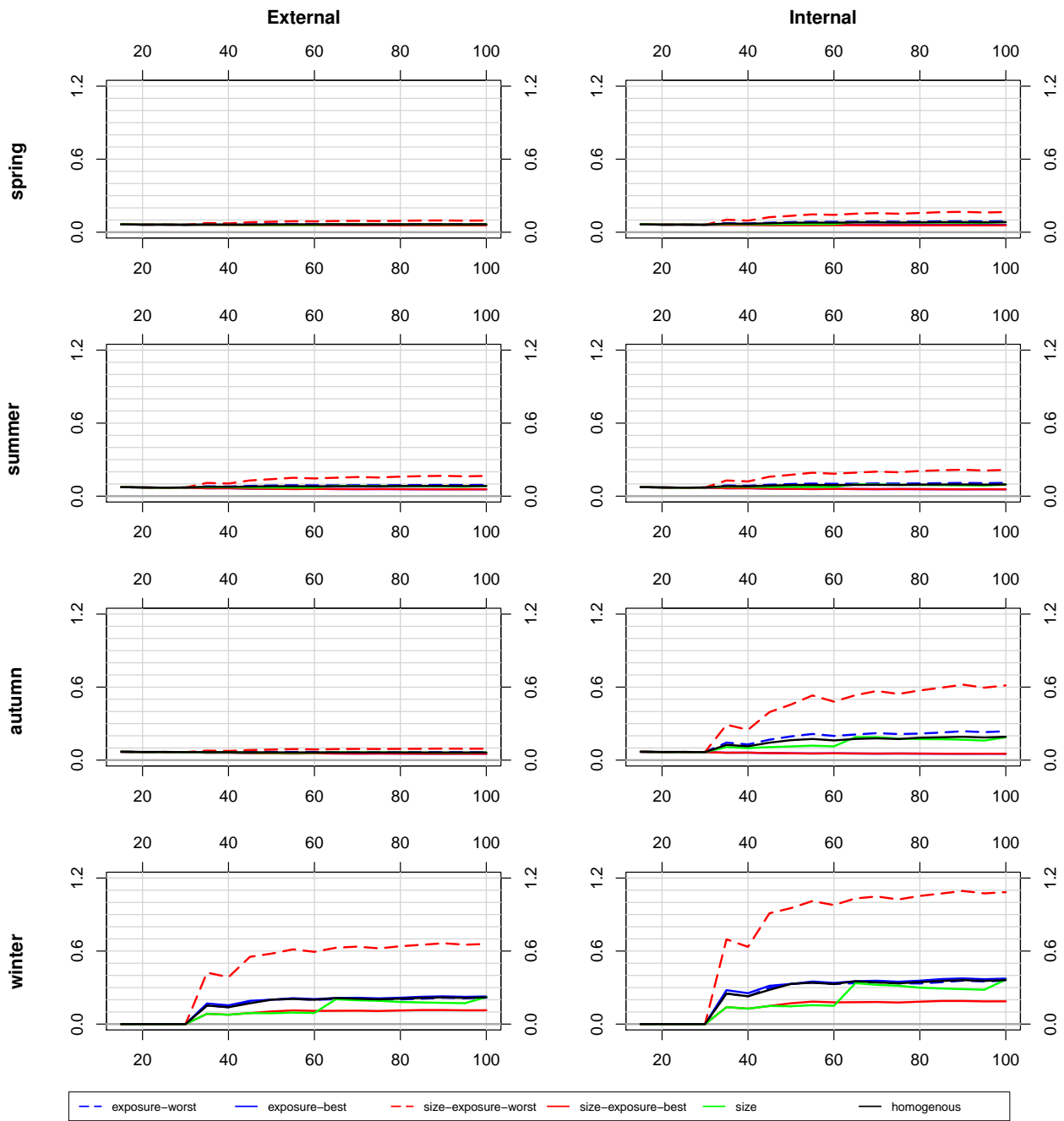
60% in autumn, 20% in summer and spring under the internal tactic, decreasing to 60% in winter, 20% in summer, 10% in
655 autumn and spring under the external tactic. Under the configuration that suffers the least damage (*size-exposure-best*),
relative differences may be close to 20% in winter, about 5% in the other seasons under the internal tactic, decreasing to
10% in winter, and about 5% in all seasons under the external tactic.

Compared to the results in the previous section, it is clear that the configuration of links matters for quantitative analysis.
To grasp whether a difference is significant, the two sources of heterogeneity need to be combined: in terms of the size
660 of farms and in terms of plot exposure.



Remark: In each figure, the x-axis shows the extent of the flood; the y-axis corresponds to the relative difference in the quantification of flood impacts compared to the baseline simulation (*no interaction*). Each column represents a different farm coping tactic.

Figure 7. Implications of the level of interactions taken into account for damage assessment (homogeneous case)



Remark: In each figure, the x-axis indicates the extent of the flood; the y-axis corresponds to the relative difference in the quantification of flood impacts compared to the baseline simulation (*no interaction*). Each column represents a different farm coping tactic.

Figure 8. Implications of the configuration of the interactions for damage assessment (Winery safe)

5 Limits to the studyDiscussion

Our analysis presents several limits that should be considered.

5.1 Importance of interactions in damage assessment

665 First, like in all modeling approaches, we have simplified some of the processes. In the present version of the COOPER model, the behavior of economic entities is representative of what we encountered in our field surveys and in past research. Economic entities show reactive behavior, i.e. they try to return as quickly as possible to the *statu quo ante*: They repair each damaged material component and whenever possible, respect the normal production process. "Real life" cases also include agents with more planned behavior, whose decisions will depend, for instance, on the level of damage incurred, their financial situation when a flood occurs, and their business plans. Moreover, agents may use tactics
670 to actively deal with floods (e.g. moving vulnerable equipment), or production disruption (e.g. in the case of wineries, borrowing/renting external equipment to enable wine production) that are beyond the scope of this article but could have an impact on our results. The impact that different agents' behaviors can have on our results and on the response of the whole system to floods constitutes a future line of research that merits attention.

Second, as mentioned above, we focussed on two specific kinds of interactions within the boundaries of the system.
675 Other interactions observed in real cases concerning farm cooperation and organization — e.g. equipment and/or labor sharing, solidarity after flood events — or farm-winery cooperation — e.g. bilateral help in the case of flooding — are not incorporated in the current version of the model. The impacts of those interactions are thus beyond the scope of the present article. The impact they may have on our results nonetheless merits further investigation and is consequently a potential line of research. Similarly, the interactions between the CWS and other entities — e.g. input/equipment providers,
680 sellers, insurers, or banks — are also outside the purview of this article, but their effects also merit further investigation.

Finally, we chose a GPS that is organized like a star, with a central element. While appropriate for the CWS, this representation does not fit some economic sectors that would be better represented by a multi-node system, or even a no-node system.

Current damage assessment at local level within complex productive systems considers agents and their material
685 entities separately but does not include the links between them. Our experiments show that this kind of practice can involve two types of bias. The first bias, i.e. the misrepresentation or absence of links, leads to underestimation of flood impacts due to inherent inaccuracy in the spreading of disturbances within the system. The second bias was less expected and is in contradiction with the arguments put forward by Penning-Rowsell et al. (2013b). It overestimates damage when failing to take interactions into account. The origin of such a bias can be traced back to the fact that, even when entities
690 are considered independently, their schedules are not taken into account. As a result, some material components could be considered to be present at two places at once, thereby leading to double accounting of some material damage.

These two types of bias can be extrapolated to other types of economic systems. Indeed, systems in which the substitution of inputs is not plausible would face the same problems in the estimation of flood damage if the interactions between

the component entities are not taken into account. For instance, this may be the case of systems organized like the CWS, in which input substitution is not permitted by the nature of the product, by rigidities introduced by contracts, or by the lack of substitutes for very specific goods, as observed in the automobile and electronic industries after the 2011 flood in Thailand (Haraguchi and Lall, 2015). The second type of bias will be found in any system in which material components move through different economic entities (basically the case in all supply chain systems). When there is no clear idea of the location of the product, and hence no thorough understanding of the production processes and schedules, there is a high probability of overestimating economic damage due to duplicate entries in an inventory.

~~Accounting for these links when characterizing the interactions in a given system therefore improves flood damage assessment. However to characterize such links can be costly in terms of information gathering. In that regard, the comparison made between our so-called *within activity* and *between activity* interactions does not enable us to judge whether some types of interactions are more important than others. The results obtained (section 4.2) show that the importance of the type of interactions depends on the season, and consequently, on the underlying production processes. However, as a general recommendation, we suggest that the type of interactions to be taken into account to finely characterize a system might be linked to how dispersed the system concerned is across a given territory: In farming systems, where productive units are composed of elements of very different nature in different locations, taking both types of interactions into account is highly recommended. In contrast, productive systems composed of entities whose means of production are concentrated in one place (e.g. wineries) may work better under the assumption that all elements are equally affected by a flood, in which case, the characterization of the *within activity* interactions may not be so vital.~~

~~The experiments we conducted~~ Our experiments also showed that if interactions are to be taken into account, they must be thoroughly characterized. ~~Indeed, our results~~ (In such regard, results in section 4.1) highlight the importance of the configuration of links between material components. These results are particularly relevant to the extent that location (thus spatial exposure), the vulnerability of individual equipment, and the rules governing links between material entities were the same across simulations. Under such conditions, current flood damage assessment would find no difference between configurations, even though the different configurations of links between entities lead to different damage intensities. ~~There is no easy way to estimate them at lower cost, as this could increase the more bias compared with the~~ To fail in properly characterizing the existing interactions within a system can lead to bias in the resulting flood damage estimation, compromising the very advantage of taking interactions into account.

The ~~application of our methodology for the economic evaluation of flood management projects requires in-depth described improvements in flood damage estimation come nonetheless at a cost in terms of information gathering. A thorough~~ characterization of the ~~links between economic entities, which, at certain levels (e.g. regional or national), may be considered too costly. However, the method can provide crucial insights at the local level, for instance, in projects that require over-flooding of certain agricultural areas to better protect areas considered to be more vulnerable. In such cases, financial mechanisms are often needed to compensate overexposed agents, and accurate assessment of interactions present in a system as the CWS can be highly resource-consuming. In that regard, the comparison made between our so-called *within activity* and *between activity* interactions does not enable us to judge whether some~~

730 types of interactions are more important than others. The results obtained (section 4.2) show that the importance of the
type of interactions depends on the season, and consequently, on the underlying production processes. Furthermore,
it appears that concerning productive units composed of elements of very different nature in different locations –as the
CWS' farms– taking both types of interactions into account is highly recommended, whereas for productive units whose
means of production are concentrated in one place –e.g. the CWS' winery– the characterization of the ~~negative effects~~
is essential to insure appropriate compensation, and ultimately the acceptability of the project. Moreover, many projects
735 also aim to promote the adaptation of exposed economic activities. In-depth knowledge of how these economic activities
are organized would help target the most effective adaptations, especially organizational ones. Our method could also
be used to enable the financial analysis of the viability of economic activities, including the risk of bankruptcy
between
activities interactions may suffice (thus, assuming that all elements in those productive units are equally affected by a
flood).

740 ~~It is also remarkable-~~

5.2 Contribution of a computational laboratory

Finally, we would like to highlight that our method ~~provides-proposes -and is based- on~~ a computational laboratory for
flood damage assessment. It enables the estimation of damage to a CWS originating from small-, medium-, or large-
scale flood events. While we did not use the same modeling approach as Koks et al. (2014), like them, we consider
745 that, as impact mechanisms differ depending on the scale of the event, this wide view has undeniable advantages over
the study of a single phenomenon. For instance, our results clearly show that, at least in the case of CWSs, contrary
to what is claimed, it is not appropriate to use *approaches that calculate production losses using a fixed share of direct*
damage (Meyer et al., 2013) for all types of events. Although this article focuses on a CWS, the development procedure
is applicable to other CPS. In this sense, the contents of this article, together with the information in Nortés Martínez et al.
750 (2019), can be used as guidelines for the development of COOPER-like models applied to other CPS.

5.3 Limits to the study

Our analysis presents several limits that should be considered.

First, like in all modeling approaches, we have simplified some of the processes. In the present version of the COOPER
model, the behavior of economic entities is representative of what we encountered in our field surveys and in past
755 research. Economic entities show reactive behavior, i.e. they try to return as quickly as possible to the *statu quo ante*:
They repair each damaged material component and whenever possible, respect the normal production process. "Real
life" cases also include agents with more planned behavior, whose decisions will depend, for instance, on the level of
damage incurred, their financial situation when a flood occurs, and their business plans. Moreover, agents may use tactics
to actively deal with floods (e.g. moving vulnerable equipment), or production disruption (e.g. in the case of wineries,
760 borrowing/renting external equipment to enable wine production) that are beyond the scope of this article but could have

an impact on our results. The impact that different agents' behaviors can have on our results and on the response of the whole system to floods constitutes a future line of research that merits attention.

765 Second, as mentioned above, we focussed on two specific kinds of interactions within the boundaries of the system. Other interactions observed in real cases concerning farm cooperation and organization – e.g. equipment and/or labor sharing, solidarity after flood events – or farm-winery cooperation – e.g. bilateral help in the case of flooding – are not incorporated in the current version of the model. The impacts of those interactions are thus beyond the scope of the present article. The impact they may have on our results nonetheless merits further investigation and is consequently a potential line of research. Similarly, the interactions between the CWS and other entities – e.g. input/equipment providers, sellers, insurers, or banks – are also outside the purview of this article, but their effects also merit further investigation.

770 Finally, we chose a CPS that is organized like a star, with a central element. While appropriate for the CWS, this representation does not fit some economic sectors that would be better represented by a multi-node system, or even a no-node system.

6 Conclusion

775 Although left aside in current practice, the introduction of explicit interactions in productive systems has a non-negligible impact on the amount of damage estimated at a microeconomic scale. The characterisation of these interactions requires the introduction of links between the material components mobilised by the productive system, the nature of which depends directly on the tasks and operations necessary for the production process. Not taking these interactions into account can lead to two opposite effects: an underestimation of damage if the propagation of disturbances is poorly represented, and an overestimation of damage if the location of the product is poorly represented. This observation does not allow us to give a general recommendation, one way or the other, to correct the estimates currently made.

780 The effort required to represent these interactions, compared to current practice, is quite substantial. It includes the acquisition of additional information, which has so far been little used in the definition of damage functions. It also involves a real effort to understand the production processes, which is in any case greater than what is required to produce the current damage functions.

785 This observation may appear to be a barrier to improving the operational practice of damage estimation, particularly in the context of economic evaluations such as cost-benefit analyses based on avoided damage, carried out on a regional or national scale. However, we believe that it deserves particular attention at a local scale. We are thinking in particular of projects that could have negative consequences in terms of exposure to flooding, which would have to be compensated for. In this case, an estimate that takes into account the understanding of the production system and its spatial exposure seems necessary to better establish any monetary estimate of compensation, and to introduce confidence with the over-flooded stakeholders. We are also thinking of all projects that aim to reduce the vulnerability of productive systems. In this respect, our approach could provide an evaluation framework and lead to a better understanding of the vulnerability of such systems.

795 In terms of perspectives, our approach, particularly in its virtual laboratory component, can make it possible to explore combinations of phenomena for which it is difficult to obtain empirical data, such as, for example, the impact of a succession of floods in close proximity, the conjunction of a flood with a market-type hazard affecting the modelled sector.

800 Our approach could also be complemented by an analysis of the resilience of the activities, by following the financial impact of floods over time and checking whether the financial situation of the activities is compatible with the continuation of their activities, or if on the contrary it seems to lead to bankruptcy. This questions a key assumption of economic analyses based on avoided damage, which implicitly assumes that the damage caused by floods is estimated, without the disappearance of the stakes that have suffered them. The relevance of this assumption should also be discussed in future work.

805 Finally, our approach could be combined with a practice of observing the impacts with the actors directly concerned. Indeed, although our analyses are based on in-depth surveys of winegrowers and managers of cooperative wineries, we can only benefit from discussing both our results and our modelling approach with the main stakeholders. This discussion could make it possible to clarify any overly strong assumptions that we might have made. It could also make it possible to give the virtual experience of events that the interested parties would not have experienced, in order to be better prepared for them. This is the ambition of a process that our team has started within the framework of the so-ii flood impact observatory (so-ii.org), with the establishment of a long-term partnership with people particularly concerned by floods.

Code and data availability. The COOPER model and the data needed to perform the present analysis are available online at the CoMSES computational model library (<https://www.comses.net/codebases/6038/releases/1.0.1/>).

815 *Author contributions.* DNM, FG, and JR developed COOPER model, DNM and FG performed the analysis and drafted the first version of the manuscript. All authors discussed the results and edited the manuscript

Competing interests. The authors declare that they have no conflict of interest.

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820 References

- Agreste: Recensement Général Agricole, Tech. rep., Ministère de l'Agriculture, 2010.
- Barendrecht, M. H., Viglione, A., and Blöschl, G.: A dynamic framework for flood risk, *Water Security*, 1, 3–11, <https://doi.org/10.1016/j.wasec.2017.02.001>, 2017.
- Battagliani, A., Barbeau, G., Bindi, M., and Badeck, F. W.: European winegrowers' perceptions of climate change impact and options
825 for adaptation., *Regional Environmental Change*, 9, 61–63, 2009.
- Bauduceau, N.: Éléments d'analyse des répercussions des inondations de novembre 1999 sur les activités agricoles des départements de l'Aude, des Pyrénées-Orientales et du Tarn, Tech. rep., Équipe pluridisciplinaire Plan Loire Grandeur Nature, 2001.
- Biarnès, A. and Touzard, J.-M.-M.: ~~La rémunération différenciée construction de la rémunération différenciée~~ du raisin dans les ~~coopératives coopératives~~ du Languedoc, in: ~~Les coopératives coopératives~~ entre territoires et mondialisation, edited by ~~J.F., D. and J.M., T. Draperi, J.-F. and Touzard, J.-M.~~, pp. 215–231, ~~L'harmattan-IESHarmattan~~, 2003.
830 ~~and J.M., T. Draperi, J.-F. and Touzard, J.-M.~~, pp. 215–231, ~~L'harmattan-IESHarmattan~~, 2003.
- Bosello, F. and Standardi, G.: A Sub-national CGE Model for the European Mediterranean Countries, in: ~~The New Generation of Computable General Equilibrium Models: Modeling the Economy~~, edited by ~~Perali, F. and Scandizzo, P. L.~~, pp. 279–308, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-58533-8_11, 2018.
- Brémond, P.: Caractérisation et évaluation économique de la vulnérabilité des exploitations agricoles aux inondations, Thèse de doctorat, spécialité sciences économiques, Université de Montpellier 1, Montpellier, France, 2011.
835
- Brémond, P. and Grelot, F.: Taking into account recovery to assess vulnerability: application to farms exposed to flooding, in: *Managing Resources of a Limited Planet*, 2012 International Congress on Environmental Modelling and Software, edited by Seppelt, R., Voinov, A. A., Lange, S., and Bankamp, D., International Environmental Modelling and Software Society, Leipzig, Germany, 2012.
- Brémond, P., Grelot, F., and Agenais, A.-L.: Review Article: "Flood damage assessment on agricultural areas: review and analysis of
840 existing methods", *Natural Hazards and Earth System Science*, 13, 2493–2512, <https://doi.org/10.5194/nhess-13-2493-2013>, 2013.
- Brouwer, R. and van Elk, R.: Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands, *Ecological Economics*, 50, 1–21, <https://doi.org/10.1016/j.ecolecon.2004.01.020>, 2004.
- Carrera, L., Standardi, G., Bosello, F., and Mysiak, J.: Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling, *Environmental Modelling and Software*, 63, 109–122, 2015.
- 845 CCMSA: Conférence de presse de rentrée de la CCMSA, Mutualité Sociale Agricole. Direction de la communication - Service Presse, last access: January 2018, 2017.
- Centre d'économie rurale: ~~R~~~~La Viticulture du Languedoc Roussillon~~ ~~Données rences technico~~-économiques ~~d'une vigne palissée en Languedoc Roussillon~~, CER France, ~~Tech.rep., 2014 edn., 2014.~~
850 Centre d'économie rurale, ~~2017-~~
~~GER: R: é~~~~La Viticulture du Languedoc Roussillon - Données technico-es~~ économiques ~~d'une vigne paliss~~, ~~Tech. rep., Centre d'é~~
~~é en Languedoc Roussillon, CER France~~ ~~économie rurale~~, ~~2014 edn., 2014.~~ ~~2017.~~
- Chambre d'agriculture Var: Action 25 du PAPI d'intention de l'Argens. Réalisation de diagnostics de vulnérabilité d'installations agricoles en zone inondable, 2014.
- 855 Chevet, J. M.: Le rôle des caves coopératives dans le regroupement de l'offre en France au XXème siècle, Tech. Rep. 2004-12, INRA-CORELA working papers, <https://www6.versailles-grignon.inra.fr/aliss/content/download/3348/35635/file/WP04-12.pdf>, 2004.

- Chongvilaivan, A.: Thailand's 2011 flooding: Its impact on direct exports and global supply chains, ARTNeT Working Paper Series 113, Asia-Pacific Research and Training Network on Trade (ARTNeT), 2012.
- 860 Cochran, H. C.: Indirect Losses from Natural Disasters: Measurement and Myth, in: Modeling Spatial and Economic Impacts of Disasters, edited by Okuyama, Y. and Chang, S. E., Advances in Spatial Science, chap. 3, pp. 37–52, Springer Berlin Heidelberg, https://doi.org/10.1007/978-3-540-24787-6_3, 2004.
- Collombat, P.-Y.: Rapport d'information fait au nom de la mission commune d'information sur les inondations qui se sont produites dans le Var, et plus largement, dans le sud-est de la France au mois de novembre 2011, 2012.
- 865 Crawford-Brown, D., Syddall, M., Guan, D., Hall, J., Li, J., Jenkins, K., and Beaven, R.: Vulnerability of London's Economy to Climate Change: Sensitivity to Production Loss, *Journal of Environmental Protection*, 4, 548–563, 2013.
- Crespi, V., Galstyan, A., and Lerman, K.: Top-down vs bottom-up methodologies in multi-agent system design, *Autonomous Robots*, 24, 303–313, <https://doi.org/10.1007/s10514-007-9080-5>, 2008.
- 870 Donaghy, K. P., Balta-Ozkan, N., and Hewings, G. J.: Modeling Unexpected Events in Temporally Disaggregated Econometric Input–Output Models of Regional Economies, *Economic Systems Research*, 19, 125–145, <https://doi.org/10.1080/09535310701328484>, 2007.
- [EEA: Corine Land Cover, European Environment Agency](https://land.copernicus.eu/pan-european/corine-land-cover), <https://land.copernicus.eu/pan-european/corine-land-cover>, 2012.
- Erdlenbruch, K., Thoyer, S., Grelot, F., Kast, R., and Enjolras, G.: Risk-sharing policies in the context of the French Flood Prevention Action Programmes, *Journal of Environmental Management*, 91, 363–369, <https://doi.org/10.1016/j.jenvman.2009.09.002>, 2009.
- FADN: Farm Accountancy Data Network, European Commission, https://ec.europa.eu/agriculture/rica/database/database_en.cfm, last access: September 2020, 2014.
- 875 Ferrarese, C. and Mazzoli, E.: Analysis of Local Economic Impacts Using a Village Social Accounting Matrix: The Case of Oaxaca, in: The New Generation of Computable General Equilibrium Models: Modeling the Economy, edited by Perali, F. and Scandizzo, P. L., pp. 85–116, Springer International Publishing, https://doi.org/10.1007/978-3-319-58533-8_5, 2018.
- 880 Field, C. B., Barros, V., Stocker, T. F., Dahe, Q., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M.: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2012.
- Folwell, R. J. and Castaldi, M. A.: Bulk Winery Investment And Operating Costs, Agricultural Research Center, College of Agricultural, Human, and Natural Resources Sciences, Washington State University, Pullman, Washington, 2004.
- FranceAgriMer: Observatoire de la viticulture française, last access: December 2016, 2012.
- 885 Grames, J., Prskawetz, A., Grass, D., Viglione, A., and Blöschl, G.: Modeling the interaction between flooding events and economic growth, *Ecological Economics*, 129, 193–209, <https://doi.org/10.1016/j.ecolecon.2016.06.014>, 2016.
- Grames, J., Grass, D., Kort, P. M., and Fűrnrkranz-Prskawetz, A.: Optimal investment and location decisions of a firm in a flood risk area using Impulse Control Theory, ECON WPS - Vienna University of Technology Working Papers in Economic Theory and Policy No. 01/2017, Vienna University of Technology, 2017.
- 890 Green, C., Viavattene, C., and Thompson, P.: Guidance for assessing flood losses, CONHAZ WP6 Final Report, Flood Hazard Research Center - Middlesex University, 2011.
- Hallegatte, S.: An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina, *Risk Analysis*, 28, 779–799, 2008.

- Hallegatte, S.: Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters, *Risk Analysis*, 34, 152–167, 2014.
- 895 Hallegatte, S. and Ghil, M.: Natural disasters impacting a macroeconomic model with endogenous dynamics, *Ecological Economics*, 68, 582–592, 2008.
- Hallegatte, S. and Przulski, V.: The Economics of Natural Disasters. Concepts and Methods, Policy Research Working Paper 5507, The World Bank, 2010.
- 900 Hallegatte, S., Hourcade, J.-C., and Dumas, P.: Why economic dynamics matter in assessing climate change damages: Illustration on extreme events, *Ecological Economics*, 62, ~~330~~–~~340~~330–340, <https://doi.org/10.1016/j.ecolecon.2006.06.006>, 2007.
- Haraguchi, M. and Lall, U.: Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making, *International Journal of Disaster Risk Reduction*, 14, 256–272, 2015.
- Hess, T. M. and Morris, J.: Estimating the value of flood alleviation on agricultural grassland, *Agricultural Water Management*, 15, 905 141–153, 1988.
- IGN: Registre Parcellaire Graphique, Institut National de l'Information Géographique et Forestière, 2012 edn., <https://www.data.gouv.fr/fr/datasets/r/dd2b148b-547d-4b22-860d-d5dc8a8d3140>, last access: September 2020, 2020.
- INSEE: Structure de l'emploi total par grand secteur d'activité en 2016, Institut national de la statistique et des études économiques, <https://www.insee.fr/fr/statistiques/2012798#titre-bloc-1>, last access: January 2018, 2016.
- 910 Jansen, J., van Ittersum, M., Janssen, S., and Reidsma, P.: Integrated Assessment of Agricultural Systems at the European Level, Policy Brief LIAISE – SEAMLESS, https://www.wur.nl/upload_mm/c/f/3/6f3b0caa-bf89-40a5-a0d9-0f9c5ad87cf5_Policy_brief_final_A.pdf, 2016.
- [Jarrige, F. and Touzard, J.-M.: Les mutations de l'organisation coopérative à travers l'évolution de ses règles: La rémunération de la vendange dans les caves coopératives du Midi, *Revue internationale de l'économie sociale*, pp. 36–478, 2001.](#)
- 915 Jenkins, K., Surminski, S., Hall, J., and Crick, F.: Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model, *Science of The Total Environment*, 595, 159 – 168, <https://doi.org/10.1016/j.scitotenv.2017.03.242>, 2017.
- Kajitani, Y. and Tatano, H.: Estimation of production capacity loss rate after the great east Japan earthquake and tsunami in 2011, *Economic Systems Research*, 26, 13–38, <https://doi.org/10.1080/09535314.2013.872081>, 2014.
- 920 Kelly, S.: Estimating economic loss from cascading infrastructure failure: a perspective on modelling interdependency, *Infrastructure Complexity*, 2015.
- Koks, E. E., Bočkarjova, M., de Moel, H., and Aerts, J. C. J. H.: Integrated Direct and Indirect Flood Risk Modeling: Development and Sensitivity Analysis, *Risk Analysis*, 35, 882–900, <https://doi.org/10.1111/risa.12300>, 2014.
- Koks, E. E., Carrera, L., Jonkeren, O., Aerts, J. C. J. H., Husby, T. G., Thissen, M., Standardi, G., and Mysiak, J.: Regional disaster 925 impact analysis: comparing Input-Output and Computable General Equilibrium models, *Natural Hazards and Earth System Sciences Discussions*, 3, ~~7053~~–~~7088~~7053–7088, 2015.
- Kreibich, H. and Bubeck, P.: Natural hazards: Direct Costs and Losses Due to the Disruption of Production Processes, Tech. rep., UNISDR GAR, 2013.
- Linghe, Y. and Masato, A.: The impacts of natural disasters on global supply chains, ARTNeT Working Paper Series 115, Asia-Pacific 930 Research and Training Network on Trade (ARTNeT), 2012.

- Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Assessment of economic flood damage, *Natural Hazards and Earth System Sciences*, 10, 1697–1724, 2010.
- Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Aerts, J. C. J. H., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Daniel, V., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Lochner, B., Logar, I., Papyrakis, E., Pfuertscheller, C., Poussin, J., Przulski, V., Thieken, A. H., Thompson, P., and Viavattene, C.: Costs of Natural Hazards - A Synthesis, Tech. rep., European research project CONHAZ, 2012.
- 935 Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfuertscheller, C., Poussin, J., Przulski, V., Thieken, A. H., and Viavattene, C.: Review article: Assessing the costs of natural hazards - state of the art and knowledge gaps, *Natural Hazards and Earth System Sciences*, 13, 1351–1373, 2013.
- 940 ~~Ministère de la transition écologique et solidaire: Atlas des Zones Inondables, last access: September 2020, 2020.~~
- Morris, J. and Brewin, P.: The impact of seasonal flooding on agriculture: the spring 2012 floods in Somerset, England, *Journal of Flood Risk Management*, 7, 128–140, <https://doi.org/10.1111/jfr3.12041>, 2014.
- Morris, J. and Hess, T. M.: Agricultural flood alleviation benefit assessment: a case study, *Journal of Agricultural Economics*, 39, 402–412, 1988.
- 945 [MTES: Atlas des Zones Inondables, Ministère de la transition écologique et solidaire, https://www.georisques.gouv.fr/donnees/bases-de-donnees/zonages-inondation-rapportage-2020, last access: September 2020, 2020.](https://www.georisques.gouv.fr/donnees/bases-de-donnees/zonages-inondation-rapportage-2020)
- National Research Council: The Impacts of Natural Disasters: A Framework for Loss Estimation, The National Academies Press, Washington, DC, 1999.
- 950 Nortes Martinez, D., Grelot, F., and Rouchier, J.: COOPER - Flood impacts over Cooperative Winemaking Systems, CoMSES Computational Model Library, <https://www.comses.net/codebases/6038/releases/1.0.1/>, version 1.0.1, 2019.
- OCDE: Étude de l'OCDE sur la gestion des risques d'inondation : la Seine en Île-de-France, Tech. rep., OCDE, 2014.
- Okuyama, Y. and Santos, J. R.: Disaster impact and input-output analysis, *Economic Systems Research*, 26, 1–12, <https://doi.org/10.1080/09535314.2013.871505>, 2014.
- 955 Oosterhaven, J. and Többen, J.: Wider economic impacts of heavy flooding in Germany: a non-linear programming approach, *Spatial Economic Analysis*, 12, 404–428, <https://doi.org/10.1080/17421772.2017.1300680>, 2017.
- Penning-Rowsell, E., Priest, S., Parker, D., Morris, J., Tunstall, S., Viavattene, C., Chatterton, J., and Owen, D.: Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal, Routledge, 2013a.
- Penning-Rowsell, E. C. and Green, C. H.: New Insights into the Appraisal of Flood-Alleviation Benefits: (1) Flood Damage and Flood Loss Information, *Water and Environment Journal*, 14, 347–353, <https://doi.org/10.1111/j.1747-6593.2000.tb00272.x>, 2000.
- 960 Penning-Rowsell, E. C., Priest, S. J., Parker, D. J., Morris, J., Tunstall, S. M., Viavattene, C., Chatterton, J., and Owen, D.: Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal, Routledge, 2013b.
- Posthumus, H., Morris, J., Hess, T. M., Neville, D., Philips, E., and Baylis, A.: Impacts of the summer 2007 floods on agriculture in England, *Journal of Flood Risk Management*, 2, 182–189, <https://doi.org/10.1111/j.1753-318X.2009.01031.x>, 2009.
- 965 Przulski, V. and Hallegatte, S.: Indirect Costs of Natural Hazards, CONHAZ WP2 Final Report, SMASH - CIRED, 2011.
- RETINA: Interviews from project Résilience des territoires face à l'inondation Pour une approche préventive par l'adaptation post-événement (RETINA), IRSTEA, 12 interviews focused on wine sector, winegrowing and/or cooperative activities, 2014-2016.

- Rollins, N. D., Barton, C. M., Bergin, S., Janssen, M. A., and Lee, A.: A Computational Model Library for publishing model documentation and code, *Environmental Modelling & Software*, 61, 59–64, <https://doi.org/10.1016/j.envsoft.2014.06.022>, 2014.
- 970 Rose, A. and Krausmann, E.: An economic framework for the development of a resilience index for business recovery, *International Journal of Disaster Risk Reduction*, 5, 73–83, 2013.
- Rose, A. and Liao, S. Y.: Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions, *Journal of Regional Science*, 45, 75–112, 2005.
- Rouchon, D., Peinturier, C., Christin, N., and Nicklaus, D.: Analyse multicritère des projets de prévention des inondations - Guide
975 méthodologique 2018, Tech. rep., MTES, 2018.
- Safarzyńska, K., Brouwer, R., and Hofkes, M.: Evolutionary modelling of the macro-economic impacts of catastrophic flood events, *Ecological Economics*, 88, 108–118, 2013.
- Santos, J. R., Yu, K. D. S., Pagsuyoin, S. A. T., and Tan, R. R.: Time-varying disaster recovery model for interdependent economic systems using hybrid input-output and event tree analysis, *Economic Systems Research*, 26, 60–80,
980 <https://doi.org/10.1080/09535314.2013.872602>, 2014.
- Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., and Lawrence, M.: HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment, *Natural Hazards Review*, 7, 72–81, 2006.
- Smajgl, A. and Barreteau, O.: Empiricism and Agent-Based Modelling, in: *Empirical Agent-Based Modelling - Challenges and Solutions*, edited by Smajgl, A. and Barreteau, O., vol. 1, *The Characterisation and Parameterisation of Empirical Agent-Based Models*, chap. 1,
985 Springer-Verlag New York, <https://doi.org/10.1007/978-1-4614-6134-0>, 2014.
- Smajgl, A. and Barreteau, O.: Framing options for characterising and parameterising human agents in empirical ABM, *Environmental Modelling & Software*, 93, ~~29–41~~[29–41](https://doi.org/10.1016/j.envsoft.2017.02.011), <https://doi.org/10.1016/j.envsoft.2017.02.011>, 2017.
- SwissRE: Natural catastrophes and man-made disasters in 2016: a year of widespread damages, Sigma No 2/2017, Swiss Reinsurance Company, Zurich, 2017.
- 990 Tesfatsion, L.: Agent-Based Computational Economics: Growing Economies From the Bottom Up, *Artif. Life*, 8, 55–82, <https://doi.org/10.1162/106454602753694765>, 2002.
- [Touzard, J.-M., Gaullier, C., and Jarrige, F.: Qualité du vin et prix du raisin. Trois lectures du changement dans les coopératives du Languedoc, *Études et Recherches sur les Systèmes Agraires et le Développement*, 32, 19–36, 2001.](#)
- Van der Veen, A., Steenge, A. E., Bockarjova, M., and Logtmeijer, C. J. J.: Structural economic effects of large scale inundation: a
995 simulation of the Krimpen dike breakage, Tech. rep., University of Twente, 2003.
- Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., Scolobig, A., and Blöschl, G.: Insights from socio-hydrology modelling on dealing with flood risk – Roles of collective memory, risk-taking attitude and trust, *Journal of Hydrology*, 518, 71–82, <https://doi.org/10.1016/j.jhydrol.2014.01.018>, 2014.
- Vinet, F.: Crues et inondations dans la France méditerranéenne. Les crues torrentielles des 12 et 13 novembre 1999 (Aude, Tarn,
1000 Pyrénées-Orientales et Hérault), *Questions de Géographie*, Éditions du Temps, Nantes, France, 2003.
- Xie, W., Li, N., Wu, J. D., and Liu, X. Q.: Evaluation of indirect loss from hypothetical catastrophes in two regions with different economic development levels in China, *Nat. Hazards Earth Syst. Sci.*, 12, 3325–3335, 2012.
- Xie, W., Li, N., Wu, J. D., and Hao, X. L.: Modeling the economic costs of disasters and recovery: analysis using a dynamic computable general equilibrium model, *Nat. Hazards Earth Syst. Sci.*, 14, 757–772, 2014.

- 1005 Yang, L., Kajitani, Y., Tatano, H., and Jiang, X.: A methodology for estimating business interruption loss caused by flood disasters: insights from business surveys after Tokai Heavy Rain in Japan, *Natural Hazards*, 84, 411–430, <https://doi.org/10.1007/s11069-016-2534-3>, 2016.

Appendix A: Mathematical annex

A1 Cost-revenue sharing rule

- 1010 In the COOPER model (Nortes Martinez et al., 2019), to split cost and revenues among associated farmers, the cooperative winery proceeds according the following rule (Touzard et al., 2001; Biarnès and Touzard, 2003; Jarrige and Touzard, 2001):

$$\underline{TC}_i = \left(\frac{F + V}{\sum_{i=1}^n q_i} q_i \right) \quad (i = 1, 2 \dots n) \quad (\text{A1})$$

$$\underline{B}_i^o = pq_i - TC_i = pq_i - \left(\frac{F + V}{\sum_{i=1}^n q_i} q_i \right) \quad (i = 1, 2 \dots n) \quad (\text{A2})$$

- 1015 Where:

- TC_i is the share of the wine-making cost in the winery for the farm i.
- B_i^o is the share of the profit in the winery for the farm i.
- pq_i is the share of revenue of the farm i.
- $\frac{F+V}{\sum_{i=1}^n q_i} q_i$ is the decomposed wine-making cost in the winery for the farm i.

- 1020
- F is the fixed (structural) wine-making cost.
 - V is the variable (operational) wine-making costs.
 - $\sum_{i=1}^n q_i$ is the total production in the cooperative winery, as a sum of the individual productions of the associated farms.
 - q_i is the production of the farm i.

- 1025 **A2 Imputation of winery's reparation costs among associated farmers**

As we stated in section refsec:model, when the cooperative winery is flooded we can differentiate two mechanisms for imputing reparation costs shares to associated farmers. The first mechanism imputes costs proportionally to the farmers' individual yields as in equation A3

$$R_i = \left(\frac{R}{\sum_{i=1}^n q_i} q_i \right) \quad (A3)$$

1030 Where:

1. R_i is the reparation costs imputed to farm i
2. R is the total monetary value of reparations
3. $\sum_{i=1}^n q_i$ is the total production in the cooperative winery, as a sum of the individual productions of the member farms.
- 1035 4. q_i is the production of the farm i.

The second mechanism imputes costs proportionally to the number of farmers because the CWS' production is lost. This mechanism comes formalized in equation A4

$$CT_i = \frac{R + F}{N} \quad (A4)$$

Where:

- 1040 1. CT_i is the total cost imputed to farm i
2. F is the monetary value of the fixed vinification costs
3. R is the total monetary value of reparations
4. N is the number of farms members in the cooperative winery

A3 Hierarchy of impacts

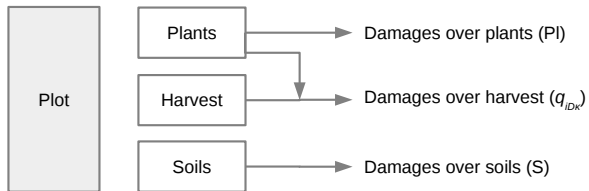
1045 Inasmuch as the flood impacts over the different material entities can be simultaneous, the effects can be summed. However, to avoid problems related to double accountability and, also, to be able to trace each impact back to its origin we have chosen to introduce hierarchic levels over flood impacts.

Flowchart A1 sketches out the hierarchy levels by entities. Before we can analyze it, we need to introduce the following new nomenclature and definitions: For each productive plot $\gamma_{i\kappa}$, owned by farm i , we can express its yield as

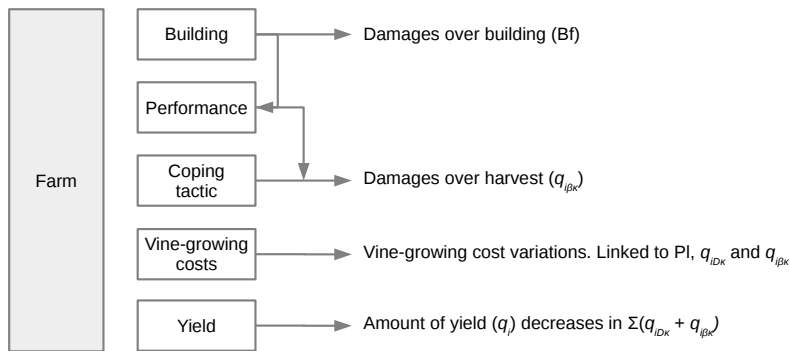
$$1050 \quad q_{iT\kappa} = q_{i\kappa} + q_{iD\kappa} \quad (A5)$$

Where:

First level



Second level



Third level

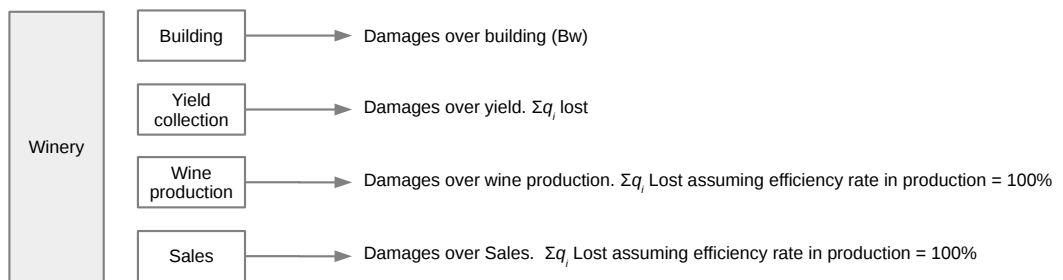


Figure A1. [Hierarchy of damages for a flood hitting entities altogether](#)

1. $q_{iT\kappa}$ is the potential harvest in plot γ_{κ} of farm i
2. $q_{i\kappa}$ is the effective harvest in plot γ_{κ} of farm i
3. $q_{iD\kappa}$ is the damaged harvest in plot γ_{κ} of farm i by the flood

1055 The term $q_{iD\kappa}$ "stores" the total of harvest damaged, whether its origin is in the direct submersion of the harvest or provoked by vine damages.

In our system, each farm i owns a number n_i of plots. Aggregating all those plots, each farm i owns a total extent Γ_i that can be expressed as:

$$\Gamma_i = \sum_{\kappa=1}^{n_i} \gamma_{i\kappa} \quad (\text{A6})$$

1060 Using equation A6, we can express equation A5 at farm level as:

$$\sum_{\kappa=1}^{n_i} q_{iT\kappa} = \sum_{\kappa=1}^{n_i} q_{i\kappa} + \sum_{\kappa=1}^{n_i} q_{iD\kappa} \quad (\text{A7})$$

Where:

1. $\sum_{\kappa=1}^{n_i} q_{iT\kappa}$ is the potential yield of farm i
2. $\sum_{\kappa=1}^{n_i} q_{i\kappa}$ is the effective yield of farm i
3. $\sum_{\kappa=1}^{n_i} q_{iD\kappa}$ is the damaged yield of farm i

1065

And the term $\sum_{\kappa=1}^{n_i} q_{iD\kappa}$, as in the individual case, "stores" the total of harvest damaged, whether its origin is in the direct submersion of the harvest or provoked by vine damages.

At the same time, we know that, depending on the coping strategy the farm adopts, we can have additional damages over the harvest. To take such effect into account, and, therefore, know the real value of $\sum_{\kappa=1}^{n_i} q_{i\kappa}$, we need to modify equation A5 introducing the new term, $q_{i\beta\kappa}$:

1070

$$q_{iT\kappa} = q_{i\kappa} + q_{iD\kappa} + q_{i\beta\kappa} \quad (\text{A8})$$

Where:

1. $q_{iT\kappa}$ is the potential harvest in plot γ_{κ} of farm i
2. $q_{i\kappa}$ is the effective harvest in plot γ_{κ} of farm i

- 1075 3. $q_{i_D\kappa}$ is the damaged harvest in plot γ_κ of farm i by the flood
4. $q_{i_\beta\kappa}$ is the damaged harvest in plot γ_κ of farm i caused by the coping strategy of the farm i

Then equation A7 becomes:

$$\sum_{\kappa=1}^{n_i} q_{i_T\kappa} = \sum_{\kappa=1}^{n_i} q_{i\kappa} + \sum_{\kappa=1}^{n_i} q_{i_D\kappa} + \sum_{\kappa=1}^{n_i} q_{i_\beta\kappa} \quad (\text{A9})$$

Where:

- 1080 1. $\sum_{\kappa=1}^{n_i} q_{i_T\kappa}$ is the potential yield of farm i
2. $\sum_{\kappa=1}^{n_i} q_{i\kappa}$ is the effective yield of farm i
3. $\sum_{\kappa=1}^{n_i} q_{i_D\kappa}$ is the damaged yield of farm i
4. $\sum_{\kappa=1}^{n_i} q_{i_\beta\kappa}$ is the damaged yield of farm i caused by the farm i 's coping strategy

Or alternatively,

1085 $q_{i_T} = q_i + q_{i_D} + q_{i_\beta}$ (A10)

Where:

$$q_{i_T} = \sum_{\kappa=1}^{n_i} q_{i_T\kappa} \quad q_i = \sum_{\kappa=1}^{n_i} q_{i\kappa} \quad q_{i_D} = \sum_{\kappa=1}^{n_i} q_{i_D\kappa} \quad q_{i_\beta} = \sum_{\kappa=1}^{n_i} q_{i_\beta\kappa} \quad (\text{A11})$$

Up-scaling a level in the production chain, we can express the amount of yield provided as input to the cooperative winery, Q_w , as the aggregation of the individual yields of its associates:

1090 $Q_w = \sum_{i=1}^n q_i = \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i\kappa}$ (A12)

Where n_i is the number of plots, γ_κ , of farm i , and n is the number of farms

Returning to flowchart A1, we can use the new nomenclature to clearly scout damages when different entities are flooded at the same time. Let us assume i) the flood hits the system in year $t = 1$, and ii) seasonal sequence is winter-spring-summer-autumn. Then, if the flood hits the system in:

1095 1. **Winter.** Impacts over plots flooded are reduced to reconditioning of soils (S)

Impacts over farms flooded include buildings (B1) and performance. If opting for *external*, $q_{i_{\beta\kappa}} = 0$, in each plot owned by flooded farms. Therefore in autumn, when harvest is done, in each productive plot owned by those farms $q_{i_{\beta}} = q_{i_{T\beta}}$, thus $q_i = q_{i_T}$ at farms level for $t = 1$. If opting for *internal*, $q_{i_{\beta\kappa}} > 0$, in each plot owned by flooded farms, so in autumn $q_{i_{\beta}} < q_{i_{T\beta}}$ in each plot owned by flooded farms, and $q_i < q_{i_T}$ at farms level for $t = 1$. In any case, vine-growing cost will vary

Impacts over wineries incorporate damages over buildings (B2) and performance. It will make the system lose Q_w of $t = 0$, but will have no effect over Q_w of $t = 1$. Since Q_w is lost, there will be no revenues for farms in $t = 1$, and the ones expected in $t = 2$ will be linked to the farms coping tactic. Wine-making cost will vary reflecting both situations.

1105 2. **Spring.** Impacts over plots flooded include reconditioning of soils (S), losses of harvest $q_{i_{D\beta}} > 0$ and vine destruction (PI)

Impacts over farms flooded include buildings (B1) and performance. If opting for *external*, $q_{i_{\beta\kappa}} = 0$, in each plot owned by flooded farms. Therefore in autumn $q_i < q_{i_T}$ in the amount given by q_{i_D} at farms level for $t = 1$. If opting for *internal*, $q_{i_{\beta\kappa}} > 0$, therefore in autumn $q_i < q_{i_T}$ too, but in the amount $q_{i_D} + q_{i_{\beta}}$. As in winter, vine-growing-cost will vary

Impacts over wineries are the same as in winter. Since in spring destruction of vines is likely to happen, the impacts over wine-making costs and revenues can last longer in time.

1115 3. **Summer.** Impacts over plots and farms are the same as exposed for spring, while impacts over wineries are reduced to reparation costs over buildings and materials (B2). Impacts over revenues and wine-making cost in $t = 2$ —and potentially further in time— will reflect the level of destruction in plots and the coping tactics chosen by farms.

4. **Autumn.** Impacts over plots and farms are the same as exposed for spring. Impacts over wineries comprise damages over buildings (B2) and performance. It will make the system lose Q_w of $t = 1$.

As we can see, in $t = 1$ eventually all production gets lost, but for several reasons:

- It exists $q_{i_{D\kappa}} > 0$ at each flooded plot. Therefore at system level we have $\sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i_{D\kappa}} > 0$ provoked by the direct impact of floods over plots
- If farm's coping tactic is *external*, then $q_{i_{\beta\kappa}} = 0$. There is no added damage by the farm, and the yield lost by the winery is:

$$Q_w = \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i_{T\kappa}} - \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i_{D\kappa}}$$

(A13)

- If farm's coping tactic is *internal*, then $q_{i\beta\kappa} > 0$, the added damage by each farm is $\sum_{\kappa=1}^{n_i} q_{i\beta\kappa}$, and the yield lost by the winery is

$$Q_w = \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i_T\kappa} - \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i_D\kappa} - \sum_{i=1}^n \sum_{\kappa=1}^{n_i} q_{i\beta\kappa} \quad (\text{A14})$$

Revenues in $t = 2$ will be null and wine-making cost will be reduced to the winery's structural cost. Due to vine destruction at plot level, as it happens in spring and summer, effects over revenues and wine-making cost are expected to last longer in time, reflecting such vine destruction.

A4 Impact calculation

Table A1 offers a more insightful overview to the calculation of impacts by comparison of a *Business as Usual Scenario* (BAU) with a *Flood Scenario* (FS).

Variable	Impact ($Imp_t = FS_t - BAU_t$)	
	Farm i	CWS
I_t	$I'_{i,t} - I_{i,t}$	$I'_t - I_t$
Q_t	$q'_{i,t} - q_{i,t}$	$\sum_{i=1}^n q'_{i,t} - \sum_{i=1}^n q_{i,t}$
R_t	$p(q'_{i,t} - q_{i,t})$	$p\left(\sum_{i=1}^n q'_{i,t} - \sum_{i=1}^n q_{i,t}\right)$
C_{vg_t}	$v_{vg_i}(q'_{i,t} - q_{i,t})$	$v_{vg_i}\left(\sum_{i=1}^n q'_{i,t} - \sum_{i=1}^n q_{i,t}\right)$
C_{wm_t}	$v_{wm}(q'_{i,t} - q_{i,t}) + F_{wm} \frac{\sum_{i=1}^n q_{i,t} - \sum_{i=1}^n q'_{i,t}}{\sum_{i=1}^n q_{i,t}}$	$v_{wm}\left(\sum_{i=1}^n q'_{i,t} - \sum_{i=1}^n q_{i,t}\right)$

Remark: $C_{vg_{i,t}} = F_{vg_i} + v_{vg_i}q_{i,t}$ | $C_{wm_t} = \frac{F_{wm}}{\sum_{i=1}^n q_{i,t}} + v_{wm}q_{i,t}$

Remark II: I_t = Investment | Q_t = Production | R_t = Revenues | C_{vg} = Vine-growing cost | C_{wm} = Wine-making cost

$q_{i,t}$ = yield of farm i at moment t | $\sum_{i=1}^n q_{i,t}$ = sum of yields of all farm $i \in [1, n]$ at moment t , where n = number of farms in CWS

p = market price of wine produced | v_{vg_i} = variable vine-growing cost farm i | F_{vg_i} = fixed vine-growing cost farm i

v_{wm} = variable cost of the winery | F_{wm} = fixed cost of the winery

Table A1. Impacts of floods over investments, production, revenues, vine-growing and wine-making costs, at individual (\forall farm i) and system's level in a moment t

As the reader can appreciate, impacts can be calculated at collective level –that is, the whole CWS– and at individual level –for each farm i associated to the CWS– at any moment t , where t represents the model's timesteps, namely the

number of seasons (not the number of years). It is worth noting that $q'_{i,t} - q_{i,t}$ in table A1 is not the same as $q_{i,D}$ in equation A10. In the equation, we refer only to the yield damaged by the flood, while $q'_{i,t} - q_{i,t}$ also includes the yield lost because of disability of an agent to perform an assigned task due to the flood. That is to say, it includes $q_{i,a}$ and Q_w . Aggregating the different components in table A1, we obtain the total impact for each individual farm i and the whole CWS as shown in equations A15 and A16:

1140

$$Imp_{i,t} = (I'_{i,t} - I_{i,t}) + (p + v_{vg_i} + v_{wm})(q'_{i,t} - q_{i,t}) + F_{wm} \frac{\sum_{i=1}^n q_{i,t} - \sum_{i=1}^n q'_{i,t}}{\sum_{i=1}^n q'_{i,t} \sum_{i=1}^n q_{i,t}} \quad (A15)$$

$$Imp_t = (I'_t - I_t) + (p + v_{vg} + v_{wm}) \left(\sum_{i=1}^n q'_{i,t} - \sum_{i=1}^n q_{i,t} \right) \quad (A16)$$

1145

That is, the impact of a flood at any moment t comes given by the differences in investment and yield/production. It is worth to point out that, at farm level, the impact also comprises the redistributing effect driven by the individual share of the winery's fixed costs. To ensure the comparability of financial flows over time, discount factors are utilized.

Appendix B: Disclosure of data sources and applications

GIS	EEA (2012)								
	IGN (2020)								
	MTES (2020)								
Statistics	FranceAgriMer (2012)	✂						✂	✂
	Agreste (2010)				✂				
	FADN (2014)					✂	✂		
Reports	INSEE (2016)								
	CCMSA (2017)								
	Centre d'économie rurale (2017)			✂					
	Centre d'économie rurale (2014)					✂			
Literature	Chevet (2004)		✂						
	Folwell and Castaldi (2004)			✂					
	Battagliani et al. (2009)					✂			
	Brémond (2011)						✂		
	Biarnès and Touzard (2003)								✂
	Jarrige and Touzard (2001)								✂
	Touzard et al. (2001)								✂
Interviews	Experts							✂	
	Winery CEOs	✂	✂						✂
	Vinegrowers		✂					✂	
		<u>Size</u> <u>Main Stages production</u> <u>Cost structure</u> <u>Financial data</u> <u>Damage function</u> <u>Sharing rules</u> <u>Behavior when impact</u>	<u>Size</u> <u>Tasks</u> <u>Cost structure</u> <u>Financial data</u> <u>Damage function</u> <u>Behavior when impact</u>	<u>Productivity</u> <u>Damage function</u>	<u>Number of plots</u> <u>Number of farms</u> <u>In/out flood prone area proportions</u> <u>Market price</u>				
	Cooperative winery	Farm	Plot	World					

Table B1. Sources of information organized by element feature