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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 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 functions[1]), 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 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 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 (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., 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 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 Przyluski, 2010; Okuyama and Santos, 2014; Przyluski 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 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

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[1] A 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.

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 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 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 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. Nevertheless, 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 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

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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 Barreteau, 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 Barreteau, 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.

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 sections. Section 2 briefly describes the interest of choosing a cooperative winemaking system (CWS) as a case study of CPS as well as the CWS itself and our data sources. Section 3 presents the model we developed to analyze how the CWS is impacted by floods. In section 4 we present both the setup and protocols followed in the experiments we conducted. The results obtained in our experiments are presented in sections 5 and 6. Section 7 contains a brief summary of the main limits of our analysis, and our final conclusions can be found in section 8.

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

2.1 Flood and agriculture

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 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). Characterizing 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 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) are very common.

A CWS is a CPS in which two types of economic agents interact: winegrowers (aka farms) and a winery. The cooperative 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.

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 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 figure 1

2.3 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 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, 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.

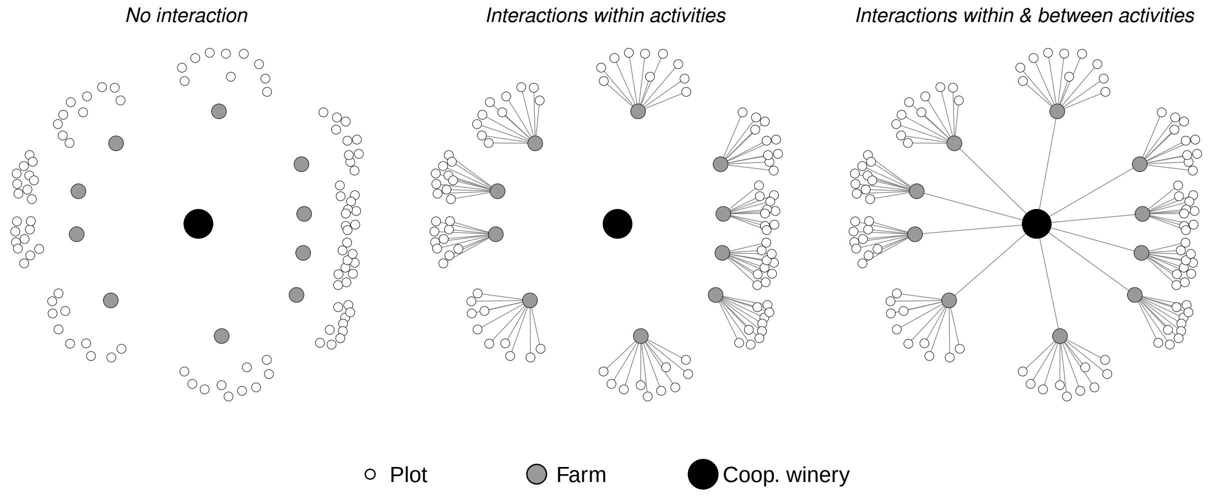


Figure 1. Shape of the kinds of interactions and network in the in the cooperative winemaking system

Financial data and data related to price, costs and cost structures came from Folwell and Castaldi (2004); CER (2014); Centre d'économie rurale (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 Ministère de la transition écologique et solidaire (2020)

3 Model

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 CoMSES computational model library (Rollins et al., 2014).

3.1 General overview

The COOPER model is built on the description of the system provided in subsection 2.2. We modeled three types of material entities: farm land plots, farm buildings and the winery's building. Each farm (understood as an 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.

3.2 Time and space representation

Each time step represents one season.

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.

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.

3.4 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 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.

3.5 Flood process I: Intensity of a flood

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

The territory is divided into two different areas: one subject to floods (flood-prone area), one not. 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.

In this study, 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.

3.6 Flood process II: Impacts of flood

Floods can have simultaneous impacts on farm plots, farm buildings and on the winery building. They first cause material damage and then disrupt the activity compared to normal processes.

3.6.1 Material damage to farms plots and associated disruptions

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, 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. Destruction of 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.

3.6.2 Cost savings at farm level

Savings in winegrowing costs are estimated in the plots in which the yield has been destroyed. Whether 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 in the plot concerned thereby saving the cost of the remaining tasks until the beginning of the following campaign.

3.6.3 Material damage to the farm buildings

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.

3.6.4 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 the winegrowing tasks cannot be carried out by the farm. The damage related to the loss of functionality depends on the farmer's coping tactics.

3.6.5 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 yield losses 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.

3.6.6 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 damages the building and completely destroys any stock present in the building at the time of the flood.

3.6.7 Disruptions due to damage to the winery building

Like disruptions in farms, the damaged winery building needs to be repaired. Until the repairs are done, the building cannot function and, depending on the season, grapes cannot be collected in the autumn, wine cannot be produced in winter and sales cannot be made in spring.

3.6.8 Cost savings at winery level

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 is worth noting that the structure of winemaking costs and the way these costs are shared among the farms 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.

3.6.9 Impact calculation

Impacts are calculated by comparing a *Business as Usual Scenario* (BAU) with a concrete *Flood Scenario* (FS). In other words, the total 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

We designed a general setup that remained fixed across simulations, and performed a twofold experiment to analyze the extent of divergence between estimating impacts with the COOPER model and current practices of damage assessment at local levels.

4.1 General setup across simulations

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

4.1.1 Simulation time span

30 years

4.1.2 Material entities

The CWS is composed of:

- One winery building (thus 1 *winery* agent).
- 50 farm buildings (thus 50 *farm* agent).
- 500 plots. The size of each plot is assumed to be 1 ha.

4.1.3 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 (buildings and plots) is the same in all the simulations. This insures that the material components of the farms are always impacted in the same way by a flood of a given extent and in a given season (see Table 1).

- 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 2).
- 150 plots (30% of 500) are also within the flood-prone area, randomly distributed within the band [10–100] (see Figure 2).

4.1.4 Other parameters

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

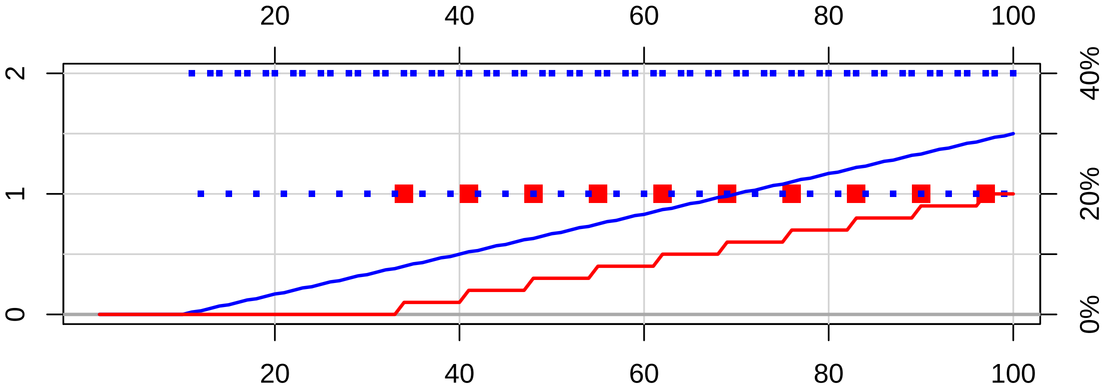
4.2 Experiment I: Influence of the presence of explicit links between material entities

4.2.1 Goal

Protocol to compare methods of flood damage estimation and the influence that they have on the resulting impact.

Table 1. 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 2. Spatial distribution of farms buildings and plots inside the flood-prone area

280 4.2.2 Configurations of links

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 3 for more information.

4.2.3 Description

To estimate the influence that the inclusion of explicit interactions between material entities has on the estimation of flood 285 damage, we sequentially simulate and compare three alternative cases (figure 1):

No interaction There are 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.

Partial interaction The damage is assessed including *within* interactions. Therefore, whereas farmers and plots have access to both their own states and each other's states, the winery only has access to its own state.

Full interaction This case accounts for interactions both within and between activities. Accordingly, all material entities in the system have access to their own states and each other's states.

4.2.4 Additional hypotheses linked to the experiment

As in two of the cases, the information on other entities' states does not flow throughout the system, several additional hypotheses are required concerning damage estimation and business disruptions.

A1 In the case of *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, 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 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 of the current practices in flood damage assessment. Under these 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 2 sums up which hypothesis applies to each case.

Table 2. Modalities of interactions and assumptions for damage estimation

Case	Assumptions
No interaction	A1 + A2 + A3
Partial interaction	A2 + A3
Full interaction	—

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4.2.5 Simulations

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 COOPER model includes stochastic processes, each flood scenario is replicated 50 times. This experimental design gives a total of 43 200 different simulations.

4.2.6 Results

The average impact resulting from each simulation is presented in section 5.

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

4.3.1 Goal

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

4.3.2 Configurations of links

Several configurations of links between material entities were simulated (see figure 3 for a schematic representation and table 3 for the main characteristics of the spatial distribution of the different configurations).

homogeneous (figure 3a) 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 3b) 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.

exposure-worst (figure 3c) 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 3d) 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 3e) 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 3f) 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.

4.3.3 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’.

4.3.4 Additional hypotheses linked to the experiment

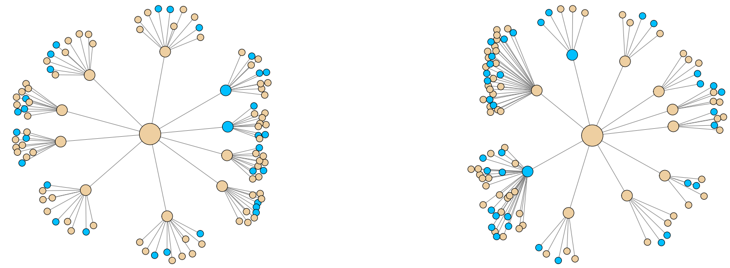
The experiment used both the *no interaction* and the *full interaction* cases from the prior experiment as baseline and actual scenarios respectively.

4.3.5 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 COOPER model includes stochastic processes, each flood scenario is replicated 50 times. This experimental design gives a total of 86 400 different simulations.

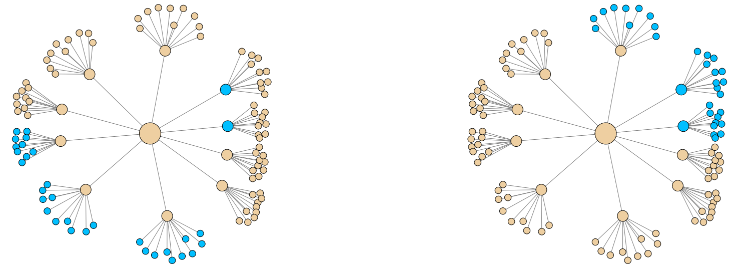
4.3.6 Results

The average impact resulting from the simulations is presented in section 6.



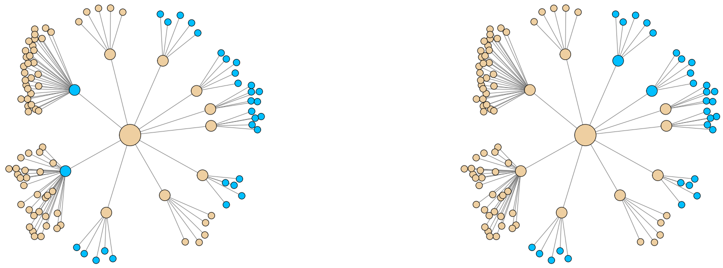
(a): Homogeneous farm size and plot exposure

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

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Table 3. Comparison of the main spatial distribution characteristics of the different configurations of links

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

5 Influence of interactions on damage estimation

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 4. 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 case in which it is not flooded (safe).

5.1 Qualitative analysis

Figure 4 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, 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.

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 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.

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 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 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 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 4, this increment is important only in winter. In this case (external tactic, winter), in Figure 4, the curves for *partial interaction* and *full interaction* match perfectly.

5.2 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 hence with the extent of the floods (because of the spatial configuration chosen, see Figure 2).

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 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, 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.

6 Influence of configurations of interactions in damage estimation

The analyses presented in section 5 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 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 5 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 5). However, in the spirit of full disclosure, we also briefly analyze the case when the cooperative winery is flooded with no additional figures. In 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).

6.1 Qualitative analysis

When the cooperative winery is not flooded, Figure 5 shows the relative differences in damage at the system level between the simulations of configurations presented in Table 3 for the case of *full interaction*, compared to the case of *no interaction*.

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 5 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.

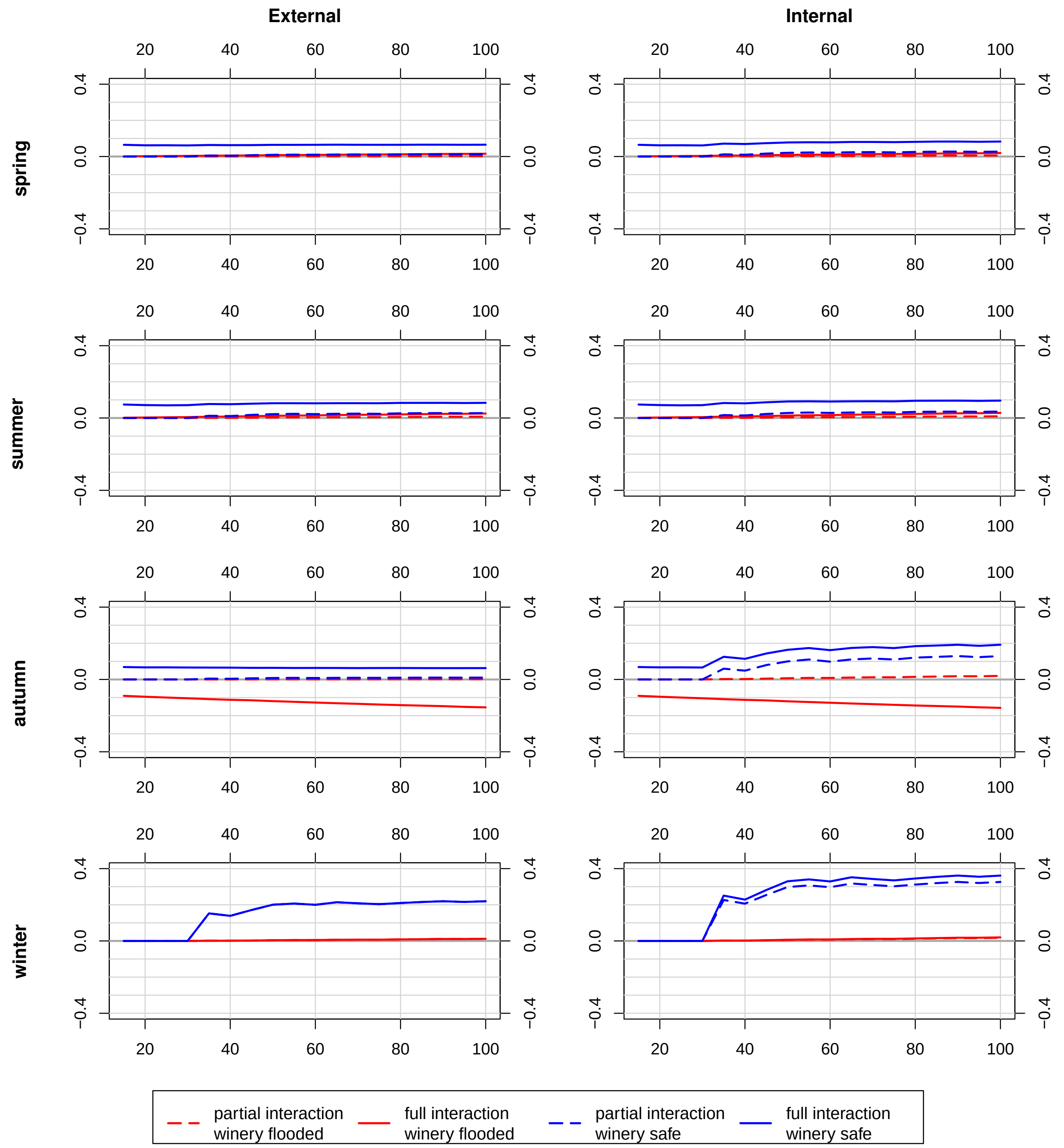
The *size* configuration (green line), which represents big farms and small farms with comparable exposure, does not introduce a major difference from the *homogeneous* configuration (black lines) in which all farms are the same size with equivalent exposure. This is also true for the two configurations 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 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 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.

6.2 Quantitative analysis

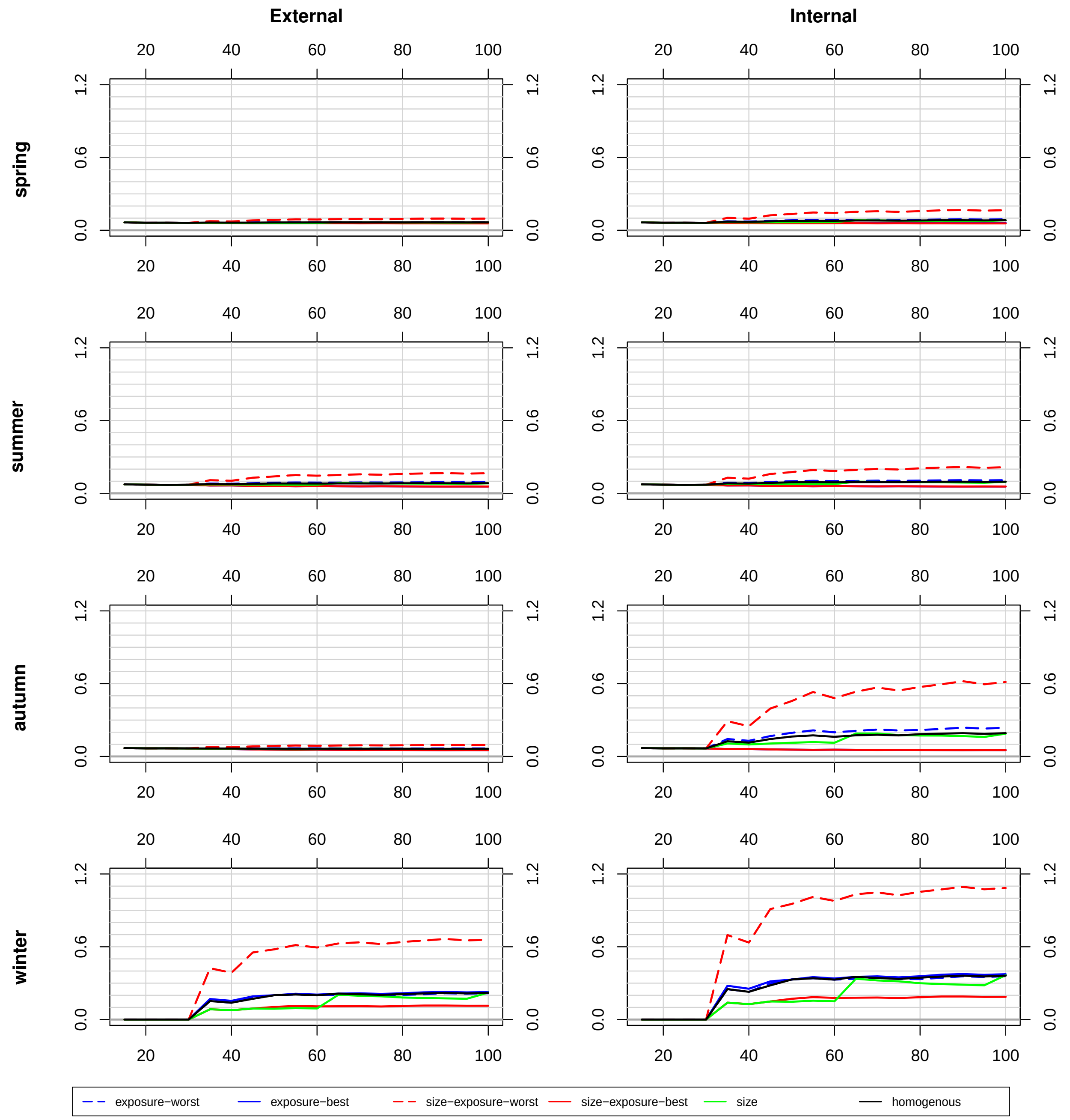
Concerning the magnitude of the differences between configurations, relative differences may be quite important. Under the configuration that suffers the most damage (*size-exposure-worst*), relative differences may be close to 110% in winter, 60% in autumn, 20% in summer and spring under the internal tactic, decreasing to 60% in winter, 20% in summer, 10% in 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 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 4. 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 5. Implications of the configuration of the interactions for damage assessment (Winery safe)

7 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 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, 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. 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.

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.

8 Conclusions

Current damage assessment at local level within complex productive systems considers 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 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 5) 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 also showed that if interactions are to be taken into account, they must be thoroughly characterized. Indeed, our results (section 6) 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 advantage of taking interactions into account.

The application of our methodology for the economic evaluation of flood management projects requires in-depth 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 the negative effects is essential to insure appropriate compensation, and ultimately the acceptability of the project. Moreover, many projects 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.

It is also remarkable that our method provides a computational laboratory for flood damage assessment. It enables 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 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 Nortes Martinez et al. (2019), can be used as guidelines for the development of COOPER-like models applied to other CPS.

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/).

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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