# CLIMATE RISKS AND FIRMS: A NEW METHODOLOGY FOR ASSESSING PHYSICAL RISKS*


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**Abstract**

This paper proposes a new methodology for assessing the exposure of Italian companies to natural hazards, which accounts for the distribution of companies' activity across different sites and locations. We apply this methodology to a sample of manufacturing companies holding establishments in Romagna. Accounting for branch offices significantly affects the quantification of flood risk exposure, particularly for large firms. Moreover, we exploit the information about the location of all the company's establishments to assess the impact of a large flood in Romagna in May 2023. This analysis shows that even highly localized natural disasters may have spillovers out of the area of interest because of the geographic distribution of company activity throughout several branches. Finally, we discuss the main issues in estimating companies' exposure to climate-related hazards and define a strategy for addressing these issues in the medium term.



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## 1 Introduction

Climate change is going to change business activity in multiple ways. First, companies must face the transitional risk coming from policies, laws, and other regulations designed to address climate change. Second, businesses must meet the increasing physical risks associated with climate change (IPCC, 2023), i.e., natural hazards such as flooding and hurricanes that can cause physical damage and disrupt business activity.

This paper focuses on the assessment of physical risks. This source of risk is particularly harmful because it can affect business in several ways. Natural hazards can cause a loss of companies' tangible assets and disrupt firms' activity for a prolonged period, eventually causing the enterprise to go bankrupt. However, assessing physical risks is challenging because the most damaging extreme events, such as floods and wildfires, are localized events. Therefore, there are several issues to consider. First, we often only know the location of the company headquarters and do not know where branch offices (e.g., manufacturing plants) are located. Second, natural hazard maps are sometimes inaccurate to assess risks to individual enterprises. Third, even if hazard maps were available, empirical evidence on the effects of natural hazards on enterprises is still too scarce to estimate potential damages from realized natural hazards.

This paper proposes a new methodology for improving the assessment of the companies' exposure to climate-related hazards by exploiting a rich set of data on companies and natural hazards. In particular, we extracted data on companies' headquarters and branch offices from the Italian business registry (InfoCamere) and retrieved the exact location of all establishments. Moreover, InfoCamere provides the number of employees by municipalities for each company. Exploiting the distribution of the employees, we can estimate the relevance of each branch for a company. The availability of the location of all establishments and the geographic distribution of the employees allow us to compute a more accurate measure of each company's exposure to natural hazards.

To provide a first assessment of this methodology, we focus on flood risk and on a subset of manufacturing firms operating (through the headquarters or the branch offices) in three Italian provinces, namely Forlì, Ravenna, and Rimini (Romagna). We restrict the attention to these three provinces and this specific natural hazard because this area has been recently hit by a severe flood that caused significant damage to business activity. Moreover, according to the PESETA IV project, in a 2°C temperature increase scenario, the damages from riverine floods are expected to increase fourfold (Feyen et al., 2020). In this paper, our aim is twofold. First, we will evaluate the exposure of manufacturing enterprises to flood risk. Second, we explore the potential of new alternative data for assessing damages from floods.

We obtain the exact location of business establishments by geocoding the addresses retrieved by InfoCamere. Then, we exploit the location to assign the exposure to floods to each company. We find that about 70% of companies in our sample are potentially exposed to floods, although to a different extent. The implications of our approach are the following. When only the headquarters' location is available, and this information is used to measure the exposure to floods, each firm can be fully or not exposed. That is an inadequate criterion for assessing the exposure of large multi-branch firms. When branch office locations are available, we can build a continuous exposure index for each company by leveraging employment information. In particular, we identify which establishments are exposed to floods. Then, we compute the weighted share of establishments at risk for each company by using the number of employees as weights. We find that 7% of companies – accounting for 56% of employees – have only partial exposure to flood risk.

As expected, accounting for branch offices dramatically affects the measurement of flood exposure for large multi-branch firms. In particular, we compare our results to the case where the exposure is measured only based on the location of the headquarters. Considering only the exposure to high hazard level, we find that 122 companies (accounting for 30% of the employees) switched from no exposure to some exposure to flood hazards, while 56 firms previously considered fully exposed to floods now feature only partial exposure.

In the second part of the paper, we explore the potential of the Copernicus Emergency Management Service (CEMS) data to quantify the damages of natural hazards. As an application, we used CEMS data to identify the companies affected by the May 17, 2023 flood in Romagna. We estimate that about 1,200 establishments have been flooded, accounting for about 18 thousand employees. Thanks to the CEMS maps, we can also calculate the intensity of the flood for the establishments that have been flooded. The median firm faced a 0.6 meter flood, but for the top 1% of the distribution, the water depth was higher than 2 meters. About 17% of the flooded companies have their headquarters out of the Emilia Romagna. This is important for two reasons. First, that shows how the effects of localized natural hazards go well beyond the area that has been hit. Second, looking only at headquarters provides a biased picture of the impact of natural hazards on business.

The aim of this paper is to start developing a better methodology for measuring Italian companies' exposure to climate-related hazards and to show how new data sources may be used to assess the damages from natural hazards. In the last part of the paper, we discuss the main issues in estimating exposure indicators and define a comprehensive strategy for addressing these issues in the medium term.

**Related Literature**: This paper is related to the literature that explores the impact of natural hazards on firms. In particular, we focus on flood risk.

Focusing on the impact of flood risk, Jia et al. (2022) find that increased flood risk has a negative impact on business demography, employment, and output. However, other studies do not find consistent evidence (Hannaoui et al., 2023). Moreover, there is a similar disagreement about the impact of floods on business performance. A few studies show that the impact of floods on business performance is positive (Leiter et al., 2009; Coelli and Manasse, 2014). This effect could be due to the recovery process following a flood event. In the recovery stage, there is often a large flow of aid from the central government to flood-affected areas. More recent studies find negative and persistent effects of floods on business performance and survival (Fatica et al., 2022; Clò et al., 2023). Severe measurement issues plague all these papers, as they cannot accurately identify firms that were hit by the flood, and they consider only companies' headquarters.[1] This paper develops a methodology to improve the identification of companies exposed to flood risk or hit by floods in the past that could be used to analyze the impact of this natural hazard on business performance. Indaco et al. (2021) analyze Hurricane Sandy's impact on New York business establishments following an alternative approach. They show that Hurricane Sandy harmed employment and affected firms' choice of location. However, their analysis is at the land lot level, not the company level.

This paper is related to recent contributions considering the impacts of physical risks associated with climate change on businesses in Italy. Meucci and Rinaldi (2022) provide an assessment of Italian banks' exposure to floods and landslides related to lending to non-financial corporations. As in this paper, Meucci and Rinaldi (2022) use data on the distribution of companies' employees by municipalities. However, they assume that employees are uniformly distributed inside the municipality and do not exploit the information about the location of the

[1] Leiter et al. (2009) identify floods at the NUTS2 level and consider all companies inside the region as flooded. Coelli and Manasse (2014) and Clò et al. (2023) follow a similar approach but at the municipality level. Fatica et al. (2022) observe floods at the NUTS3 level and classify as flooded those firms located in an area with ex-ante high flood risk.

establishments. Frigo and Venturini (2023) geolocate the addresses of headquarters and branch offices for a representative sample of Italian firms (INVIND). Differently from this paper, they explore the determinants of companies' propensity to insure against natural hazards. Finally, Banca d'Italia (2023) quantifies the potential economic impact of the May '23 flood in Emilia Romagna on companies. However, they identify flooded firms based only on the location of headquarters and use flood maps that are less accurate compared to those we used in this paper.

The paper is organized as follows. Section 2 describes the data sources and the steps we follow to construct our dataset. Section 3 illustrates the methodology we adopt for measuring the exposure of firms to flood risk and the main results. Section 4 reports our analysis of the impact of the May '23 flood on business in Emilia Romagna. Section 5 discusses the next steps to improve our analysis and extend the coverage to the universe of Italian companies. Finally, Section 6 concludes.

## 2 Data

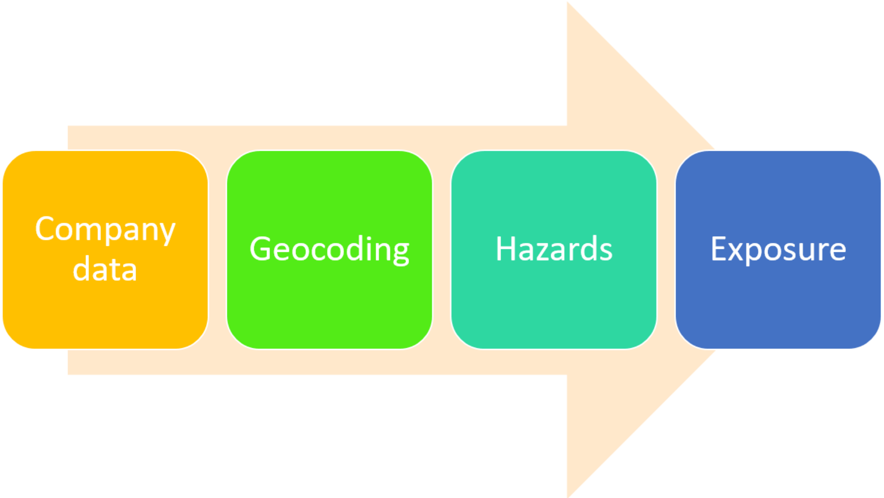
We developed indicators of companies' exposure to physical risks according to the workflow described in Figure 1. First, we gathered data on companies. In particular, we collected the addresses of the headquarters and branch offices. Second, we used the addresses to retrieve the geographic coordinates of each business premise. Third, we assigned to headquarters and branch offices their exposure to physical risks by exploiting the geographic coordinates. Fourth, we assembled the information on headquarters and branch offices to build the indicators. We will discuss the first three steps in this section and the fourth step in section 3.

### *2.1 Data on companies*

Our primary data source on companies is the Italian business register, a public register maintained by InfoCamere. The business register – hereafter InfoCamere – reports all the information relating to companies headquarters (*Sede Legale*, HQ) or branch offices (*Unità Locali*, BO) in Italy.[2] From InfoCamere, we retrieve the following company data: the name, the VAT

[2]Branch offices correspond to a variety of productive sites, e.g., deposits, factories, and shops, whereas headquarters indicate the official location that the company has declared for fiscal and legal affairs.

Figure 1: Workflow for assessing companies' exposure to flood risk




*Note:* The chart illustrates the main blocks of our methodology. Company addresses are extracted from the InfoCamere dataset. Then, companies' establishments are geolocated with an external service so that they can be joined with hazard maps to obtain an exposure indicator.

code, the NACE code, the type of company, the date of establishment and the date of termination, and the address of each establishment, either headquarters or branch office. For branches, we know the typology of establishment (e.g., manufacturing plant or warehouse). Moreover, the dataset reports the number of employees by municipality for each company at the end of the year. Therefore, when firms only own one establishment in a municipality, we know the number of employees for that premise.

This report focuses on manufacturing firms holding either the headquarters or at least one branch office in three Italian provinces hit by a severe flood in May 2023: Forlì-Cesena, Ravenna, and Rimini(*Romagna* region). We will refer to this region as the *area of interest* in our study. The dataset includes all establishments of companies that, despite being headquartered outside the area of interest, own local units inside of it. Conversely, we also take into account units located outside the area of interest that belong to companies headquartered within the area of interest. The dataset also includes data points outside the area of interest, namely the headquarters of local units in the area of interest or branch offices owned by companies headquartered in the area of interest. We dropped companies without employees.[3]

All companies considered in this study were in activity as of December 31, 2022, operating mainly in the metal, minerals, and food processing sectors (Table A1). The dataset includes 4,157 companies (table A2). Of these enterprises, 146 are headquartered outside the area of

[3]We dropped 79 headquarters and branch offices because they were outside of Italy because the risk maps employed in the following only cover the national territory. Moreover, we exclude companies with establishments in the area of interest but without employees.

interest (but within Italy). The share of companies holding secondary branches is about 30%, and they own about 4,400 branches. These companies are highly relevant when we look at the aggregated economic activity, as they are larger than those with a single premise and account for 73% of the employees as of December 31, 2022.[4] Moreover, about half of these companies hold establishments in more than one province. Finally, focusing only on the companies for which we can retrieve the balance sheet from the CERVED dataset, companies with branch offices account for about 80% of production and tangible fixed assets.

Table A3 reports additional summary statistics about the size – measured in terms of employees – and the age of companies. About 90% of companies have less than 50 employees, and about 60% of companies are 20 years old or older. Companies outside Romagna tend to concentrate on higher employee numbers and age bins because those companies must have at least a secondary unit. Looking at branch typology (Table A4), half of the secondary units are classified as stores and deposits or factories. Factories, instead, account for about 12% of all branches. We consider all branch typologies because, as we will show in Section 3, only the largest branches will matter for quantifying the exposure to natural hazards.

Our dataset has some limitations. A minor drawback is that some companies may have branch offices that we do not observe.[5] However, using the data of employees by municipalities, we observe that in nearly all cases where a firm reports employees in a city, we also have a branch office (or the headquarters). Second, the InfoCamere dataset reports the number of employees by municipality instead of the company site. Therefore, for about 20% of headquarters or branch offices, we do not have the exact number of employees, and we estimate it by assuming that the employees of a company inside a municipality are uniformly distributed across all establishments. Finally, we do not know if the company owns the site or if it rents it. This information is essential to estimate the potential damages more accurately.

We will discuss how to address these issues in Section 5.

### *2.2 Geolocation*

Most natural hazards (floods, landslides, wildfires, and windstorms) are localized events, and depending on the shape of the terrain, there may be discontinuities in exposure to these hazards

[4] This statistic is influenced by the presence of a few large firms in the dataset. Considering the Italian manufacturing sector, companies with branch offices account for 64.3% of employees.

[5] The information on branches is available only for companies that have updated their status in the business registry since 2020. Since we downloaded the data at the end of November 2023, it is reasonable to assume that we have almost complete coverage for active businesses.

even within a small area. For example, the exposure to flood risk is very high near a river, but depending on the slope of the land, the risk may shrink very quickly by moving away. For this reason, having a very accurate geolocation of business establishments is crucial.

For this report, we tested three geocoding services: Google Maps, TomTom, and OpenStreetMap. Google Maps and TomTom are pay-as-you-go services, while OpenStreetMap is free.[6] To assess the reliability of these three services, we verified their accuracy on a sample of 100 randomly chosen addresses for which we know the correct location. Based on this evaluation, the most accurate service is Google Maps (Table A5). The precision of Google Maps is maximum when the quality of the coordinate estimate is classified as *rooftop* (about 90% of the addresses in the sample).[7]

On top of a manual validation on a small sample of addresses, we evaluated the quality of the output by using three approaches. First, we analyzed the accuracy metrics reported by Google Maps. Google Maps matches the exact address in 78% of cases (Figure A1a). In 16% of cases, the coordinates refer to the centroid of the street or a bounded area. This performance is excellent because the quality of addresses is sometimes low, and house numbers can be missing. Second, we verified that the coordinates fall within the correct municipality using the Istat municipal boundaries. We found that only 2.4% of times the municipality corresponding to the coordinates is incorrect. Third, we used a set of land cover maps to identify in what kind of areas the coordinates of the company's establishments fall. This check shows that the coordinates correspond to industrial sites or roads in 67% of the cases or sparse residential settlements in 17% of cases (Table A7). In 6% of cases, the enterprise's location is in urban residential areas because the establishments may be headquarters or offices.

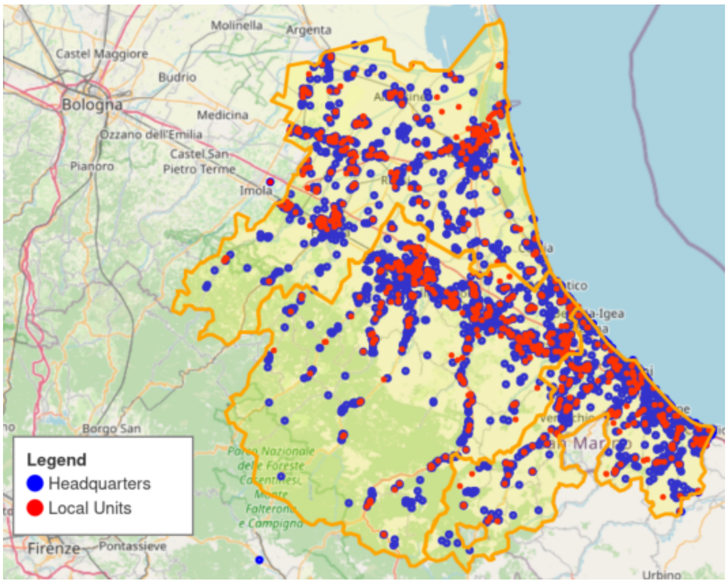
We also did a specific analysis of the precision of OpenStreetMap compared to Google Maps. This is important because OpenStreetMap is widely used for geocoding addresses.[8] We computed the distance between the locations recovered with Google Maps and OpenStreetMaps (Table A6). We found that this distance is on average very small in the case of our area of interest and more generally in Emilia Romagna. Unfortunately, the quality of OpenStreetMap

[6]Google and TomTom expose their services via Application Programming Interface (API): the programmer sends a request to the server and gets back an answer. Beyond a threshold, each request to the API has a cost.

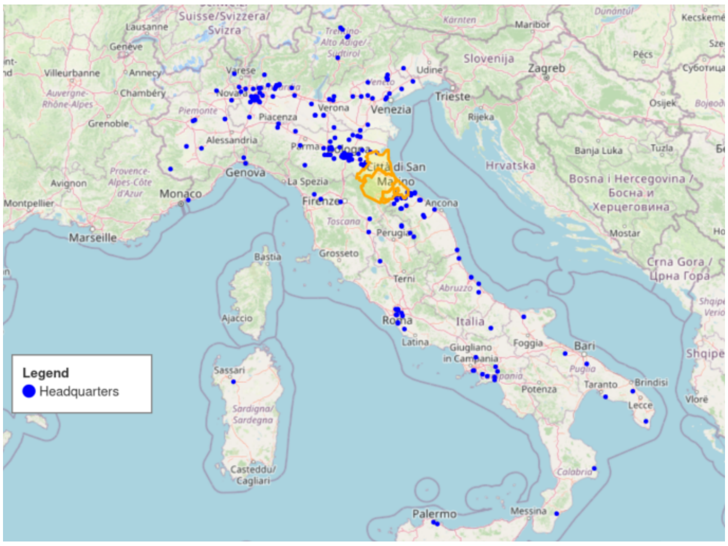
[7]The output of Google Maps has four possible levels of precision: *rooftop* means that the result matches the exact address; *range interpolated* and *geometric center* indicate that the result refers to either the centroid of the street or a bounded area (i.e., *zona industriale* or *contrada*) possibly because the street number is missing; *approximate* indicates that the precision of the result is possibly low.

[8]For example, the ECB uses OpenStreetMap to retrieve the location of all firms in the Register of Institutions and Affiliates Database (RIAD).

Figure 2: Companies' location




(a) Establishments inside the area of interest




(b) Headquarters in other provinces

*Note:* The chart displays the location of companies' establishments. Panel (a) focuses on all establishments inside the area of interest, namely the provinces of Forlì, Ravenna, and Rimini. Panel (b) shows the headquarters of companies that hold establishments in the area of interest but are located outside.

is lower outside Emilia Romagna since house numbers are generally unavailable. Considering Emilia Romagna, we match the exact address 88% of times, and the average distance from the Google Maps location is about 30 meters. Considering the other regions, instead, we match the exact address 46% of times.[9]

Figure 2a reports the distribution of headquarters and branch offices in the area of interest.

[9] Frigo and Venturini (2023) use OpenStreetMap and fail to geocode establishments' addresses in about 30% of cases. Emilia Romagna is, up to our knowledge, the only region that provides the coordinates of all street addresses. This information was probably used by the contributors to OpenStreetMap to improve its quality.

Figure 2b displays the headquarters of companies that hold establishments in the area of interest but are located outside. Figure 2b remarks that localized natural hazards may have significant impacts even far away from the area of interest because of the spatial distribution of companies.

### *2.3 Hazards*

Climate risk data usually come as maps reporting the likelihood and the expected intensity of a climate event or natural disaster occurring in a given location.[10] This report focuses only on flood risk for three reasons. First, flood risk is the most concerning climate-related physical risk in Europe (Feyen et al., 2020). According to ESRB (2021), "riverine floods are the most economically relevant widespread climate risk driver in the EU over the next two decades." Second, quantifying flood risk exposure requires a very accurate measurement of the location of business establishments. Third, a devastating flood hit the provinces of Forlì, Ravenna, and Rimini in May 2023. Then, by focusing on floods, we can analyze both the potential exposure of the companies – by exploiting hazard maps – and the ex-post consequences of a flood in the same area – by using accurate maps of flooded areas.

A crucial step of this project is the choice of hazard maps. Flood hazard maps, for example, integrate observations of past events with model simulations that consider the river network, precipitations, surface characteristics, and land cover. Therefore, these maps are the output of assumptions and specific model features, and different maps may provide significantly different results on companies' exposure to floods. We mention two important features of hazard maps. First, they can be based only on past observations, or they may also account for climate change scenarios. Including projections about climate change adds further uncertainty about the output of the simulations. Second, models have different precision because they serve different purposes. Global or continental hazard maps are coarse in modeling regional specificities because they aim to compare overall exposure and risk in different regions under standardized criteria. Regional models, instead, are designed for a specific area and cannot be easily extended to other areas. These models are more accurate than global or continental models. However, developing regional models is expensive.

Focusing on floods, there are at this moment two possible data sources: (*i*) ISPRA produces national maps based on the assessments of regional authorities (Trigila et al., 2021); (*ii*) JRC

[10] Geospatial data are typically represented in one of two types: vector or raster. Vector data represents geographic data symbolized as points, lines, or polygons. Raster data represents a given geographic area as a matrix of cells, each containing an attribute value.

builds harmonized European maps (Dottori et al., 2022). Both sets of maps are based only on past observations and do not account for future climate change scenarios. We used ISPRA maps for two reasons. First, JRC hazard maps have significant limitations regarding coverage (Loberto and Spuri, 2023). The JRC model considers only the network of main rivers and fails to assess the flood hazard close to minor rivers. The recent flood in Romagna – discussed in section 4 – is an example of why this is a serious pitfall. Moreover, the JRC model does not account for adaptation or mitigation infrastructures, i.e., leeves. These limitations cause a severe measurement error in the Italian case. Second, international research institutes building global or continental models, such as the JRC, must apply a harmonized methodology for different countries, possibly overlooking relevant national specificities. This approach is correct for developing a broad overview of physical risks but is inappropriate for our project.

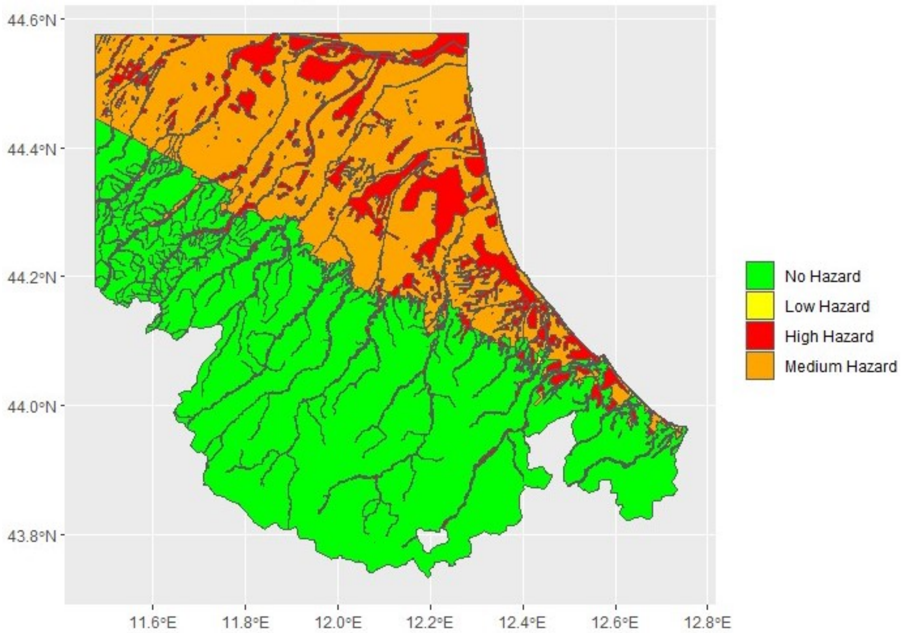
ISPRA provides three vector flood maps (Figure 3). Each map corresponds to a different likelihood of a flood event: low, medium, and high probability. In this setting, the probability is measured in terms of the return period, defined as the average time between two floods. For example, a 100-year flood has a 1/100 or 1% chance of being observed in any year. For each probability level, the data includes the boundaries of the risky areas. In low (***l***) probability zones, the return period is 500 years; in medium (***m***) probability zones, it is 100-200 years; finally, in high (***h***) probability zones, it is 20-50 years. These intervals are chosen according to Directive 2007/60/EC of the European Parliament and Council, which aims to establish a framework for assessing and managing flood risks. In addition to these levels, we will also refer to no-risk (***n***) areas wherever a geographic point is not covered by any flood probability map. We will use the ISPRA maps to identify which headquarters and branch offices are within a flood-prone zone for each likelihood level.

It is worth remarking that hazard levels are not spatially exclusive, meaning that ISPRA classifies areas as being exposed to a given *or lower* level of hazard; if an area is classified with a high probability of floods, it is by definition also exposed to medium and low risk (see Loberto and Spuri, 2023, for more details). Therefore, high (medium) probability areas are always included in medium (low) probability ones. However, in the following we will focus on the highest level of probability to which a geographic point is exposed, meaning that when we evaluate the extent of a low probability region we will subtract all portions exposed to medium and high risk.[11]

[11]Suppose that region $i$ overlaps ISPRA areas $L_i$, $M_i$ and $H_i$ at low, medium and high probability of flood, respectively, Then we will consider as being exposed to low probability only those points (and buildings) of $L_i$

Unfortunately, the ISPRA maps feature important drawbacks. First, flooding zones are identified by regional authorities (*Autorità di Bacino*). These authorities do not follow a harmonized approach, hindering regional comparability. Second, the ISPRA maps do not report information about water depth, which is crucial for estimating expected damages from floods. Third, regional authorities are forced to adopt risk management measures for flood-prone areas. In particular, planning regulations are more restrictive in flooding zones. For this reason, the definition of flooding zones could be influenced by political economy considerations (Jia et al., 2022).[12]

Figure 3: Flood hazard in Romagna




*Note:* The chart displays the flood hazard maps of Romagna produced by ISPRA. Flood-prone areas are in yellow (low hazard), orange (medium hazard), and red (high hazard).

Figure 3 shows the flood risk level map for the Romagna region, which is the area of interest in our analysis. About 50% of the region is exposed to the medium to high risk. Mountain regions (to the south) are generally spared, except for areas close to river beds. Areas exclusively exposed to low-risk levels are limited, meaning that there is often a sharp transition from safe to medium-risk areas.

not overlapping with $M_i$ and $H_i$

[12]This problem is also present in other countries. For example, the Federal Emergency Management Agency (FEMA) develops maps of flood areas that significantly impact insurance rates in the United States. For this reason, politicians and homeowners have the incentive to fight the definition of an area as flood-prone.

### 2.3.1 Emergency Mapping - CEMS

Hazard maps are the tool for assessing expected damages. In addition to these maps, we used a second set of geospatial data to evaluate the actual damages from floods. In particular, the recent increased availability of satellite data and the development of sophisticated hydraulic models make it possible to estimate the impacts of past floods. We exploit an accurate set of maps of flooded zones in May 2023 developed by the Copernicus Emergency Management Service (CEMS). CEMS is a service of the Copernicus project that can be activated by national or regional administrations in case of natural disasters. CEMS uses satellite imagery and other geospatial data to provide mapping services crucial for coordinating activities during an emergency (Rapid Mapping) or different phases such as prevention or recovery (Risk and Recovery Mapping). We will use the Risk and Recovery Mapping product released by CEMS in mid-July because of the higher accuracy compared to maps released for the Rapid Mapping. These maps allow us to identify flooded areas and estimate water depth. Therefore, we can identify companies that were hit by the flood and get a proxy of the extent of the damage. More information on CEMS can be found in Appendix B.

## 3 Measuring the exposure to flood risk

Following the workflow discussed in the previous section, we end up with a dataset reporting the level of exposure of each establishment to flood risk. Based on this data, we can build two sets of indicators:

- regional indicators to assess the exposure of manufacturing to flood risk for a given area
- company-level indicators to measure the company's exposure

Their exact formulas will be introduced in the next paragraphs. These indicators assign importance to a specific region or enterprise based on the number of workers they host and not on other economic variables such as output, revenue, or asset value. We consider all local branch typologies and not only factories. However, since we use employee number as weight for aggregating different establishments, branch typologies that accomodate large number of workers (e.g. factories) will affect indicators more than less relevant sites (e.g. warehouses).

### 3.1 Geographical indicators

The first set of indicators aims to measure the potential exposure of manufacturing activity to floods in a given area. We develop indicators down to the municipal level, as data on the distribution of enterprise employees are by municipality. However, we also estimate employees by business location. Therefore, it is possible to make more granular estimates, e.g. zip code level.

A straightforward indicator to assess the risk profile of region $i$, hosting a set $\Theta(i)$ of headquarters and branch offices, is the number of employees exposed to a given (but not higher - see Section 2.3) level $k$ of flood hazard, $N_k^i$:

$$N_k^i = \sum_{j \in \Theta(i)} W^{j,i} \mathbf{I} \{\text{Hazard level of } j = k\}) \tag{1}$$

The indicator in expression (1) is the sum of the number of workers $W^{j,i}$ over each establishment $j \in \Theta(i)$ exposed to the hazard; $\mathbf{I} \{\text{Hazard level of } j = k\})$ is an indicator function equal to 1 if the hazard level is $k$ – where $k$ can be no-risk ($N_n^i$), low ($N_l^i$), medium ($N_m^i$), or high ($N_h^i$). A slightly different version of this indicator is obtained if we drop the distinction between hazard levels:

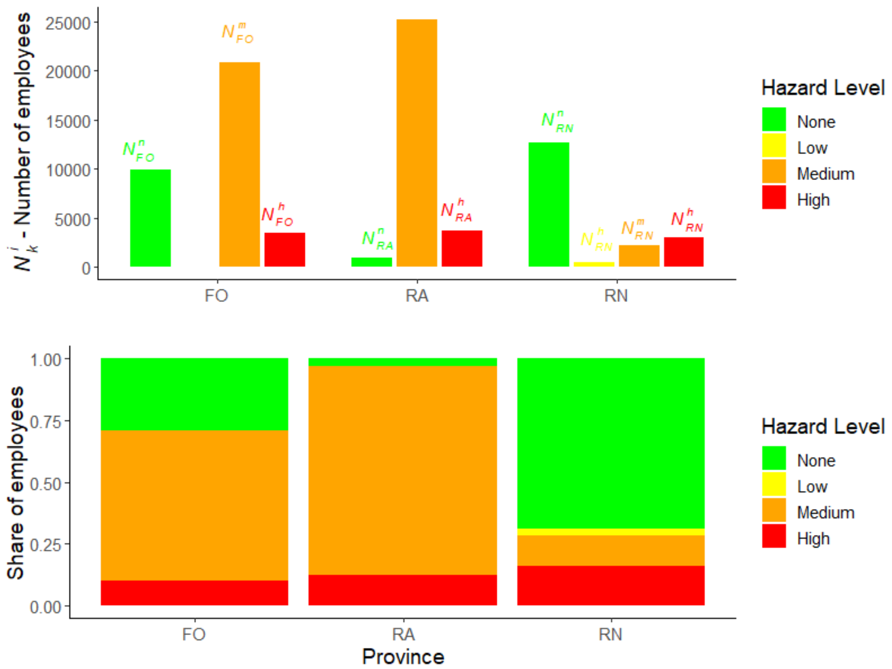
$$N^i = \sum_{j \in \Theta(i)} W^{j,i} \mathbf{I} \{\text{Hazard level of } j \neq n\}) \tag{2}$$

The indicator in 2 measures the number of employees exposed to floods, independently of the hazard level. These indicators are more informative than the bare number of companies' establishments exposed because they consider an establishment's importance (as measured by the number of employees) for the production activity.

Figure 4 shows indicator (1) when computed at the province level ($i$ = FO, RA, RN), while Figure 5 shows the same indicator for the biggest municipalities in the area of interest. The bottom part of each Figure shows the share of workers subject to each hazard level. Indicator (2) is not shown but can be easily visualized as the sum of the yellow, orange, and red bars.

The indicators lead to the following considerations. First, in the provinces of Forlì and Ravenna, the majority of workers in the manufacturing sector are exposed to medium to high flood risk levels; this percentage approaches 100% in Ravenna. Second, Rimini municipality has the lowest rate of workers at risk but also the highest rate (about 35%) of workers in areas subject to high flood hazard (return time 20-50 years), an observation which is corroborated by

Figure 4: Flood risk in Romagna




*Note:* The chart reports the indicators of exposure to flood hazard at the province level in Romagna. The upper plot displays the number of employees by hazard level in equation (1). The bottom plot shows the share of employees per hazard level.

the evidence of two flooding events affecting urban areas in the last 50 years (1976 and 1996).

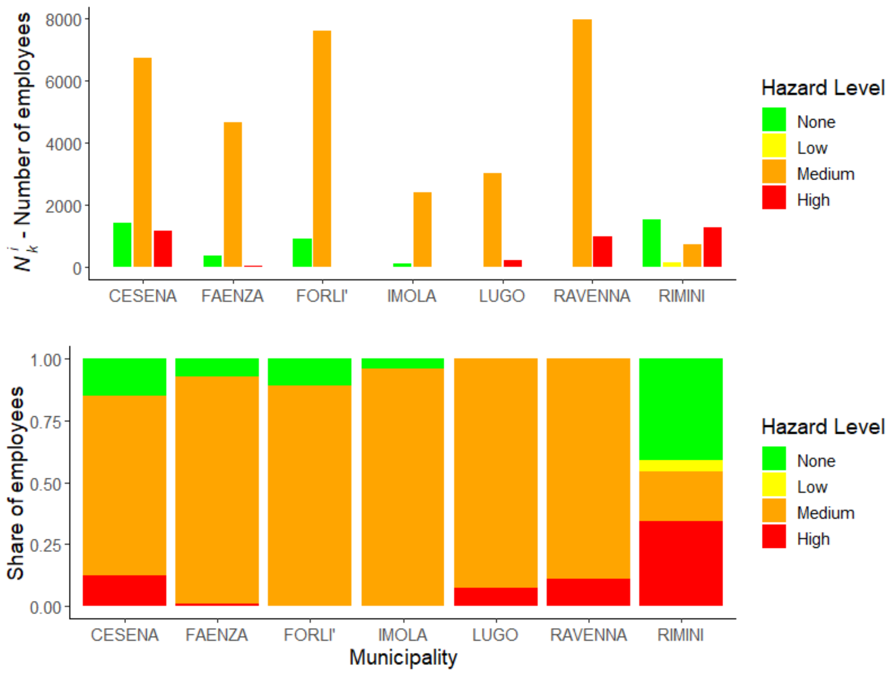
The pitfall of indicators in (1) is that they are specific to a hazard level. Indicators in 2, instead, do not differentiate across different hazard levels. Therefore, a comprehensive assessment of the risk incurred by a zone requires a joint consideration of the exposure to all the hazard levels. For this reason, we also propose the following synthetic indicator, which we name *Exposure* ($E^i$), to synthesize in a single number the exposure of a region $i$ to flood risk:

$$E^i = \sum_{k \in \{l,m,h\}} S^i_k * f(k) \tag{3}$$

where $S^i_k$ is the share of employees exposed to hazard level $k$ (but not to higher hazard levels) in region $i$, and $f(k)$ is a positive monotonic function of the hazard level. We assume $f(n) = 0$, $f(l) = 1$, $f(m) = 2$, and $f(h) = 3$. Therefore, the indicator ranges between 0 (no exposure) and 3 (all employees are in high-risk zones).

The Exposure indicator at the municipality level is shown in Figure 6. The map on the left shows an obvious similarity to the one shown in Figure 3; however, the Exposure indicator takes into account the distribution of economic activities across the territory and can better reflect the actual hazard level wherever a geographic entity is fragmented into many different

Figure 5: Flood risk in the largest municipalities in Romagna



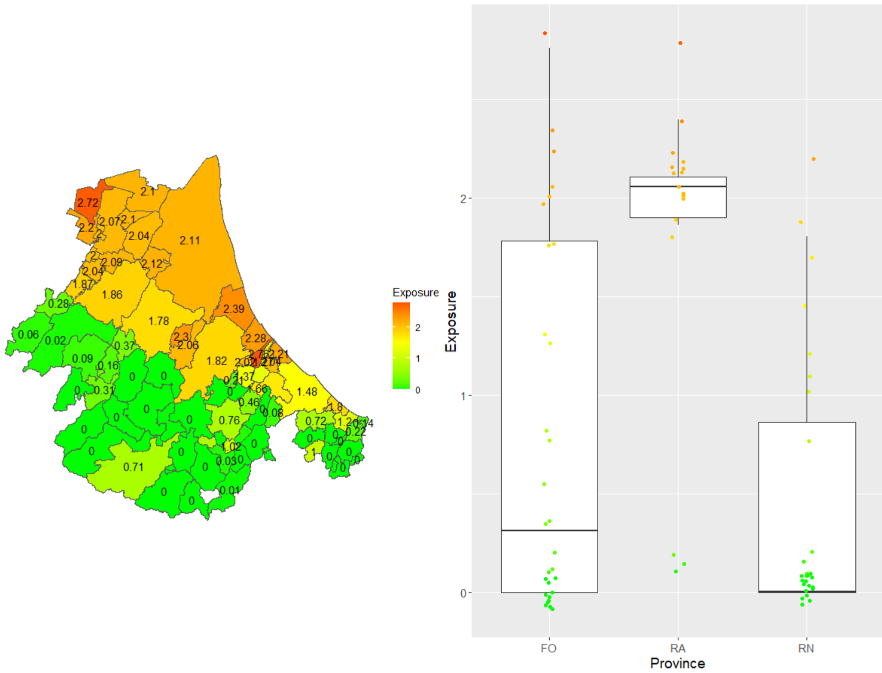

*Note:* The chart reports the indicators of exposure to flood hazard in the largest municipalities in Romagna. The upper plot displays the number of employees by hazard level in equation (1). The bottom plot shows the share of employees per hazard level.

risk areas. The right-hand plot shows how the indicator is distributed across municipalities in the three provinces. The municipalities with the highest Exposure are Gatteo ($E$=2.76) and Conselice ($E$=2.72), while many municipalities in the southern area have null exposure.

Finally, we compared our results with some statistics on the exposure of manufacturing activity based on the 2011 Census. Up to now, the 2011 Census is the most granular data source on business activity publicly available, and ISPRA uses it to compute the exposure of firms to flood risk. From Census data, we retrieve the number of employees by NACE sector and census block (*sezione di censimento*). Then, following the ISPRA approach, we computed the share of each census block's area exposed to flooding for a given hazard level. By assuming a uniform distribution of employees within the census block, we calculated the indicator in (2) at the census block and municipality level and, based on this, the share of employees exposed to any flood hazard.[13]

[13]The main pitfall of this comparison is that the census data are about ten years old, while the companies extracted from the InfoCamere dataset correspond to very recent data points. Indeed, Figure A2 shows that several municipalities show a sizeable fluctuation in the total number of manufacturing employees between 2011 and 2022. In particular, in some municipalities, the number of employees seems to experience an increase (Cesena and all data points above the bisector), while in many others (Forlì), it seems to decrease. However, since we observe fluctuations in both directions and most municipalities lie close to the bisector, we tend to exclude the presence of a systematic discrepancy between the two measurements and attribute the differences to the local evolution of the manufacturing sector.

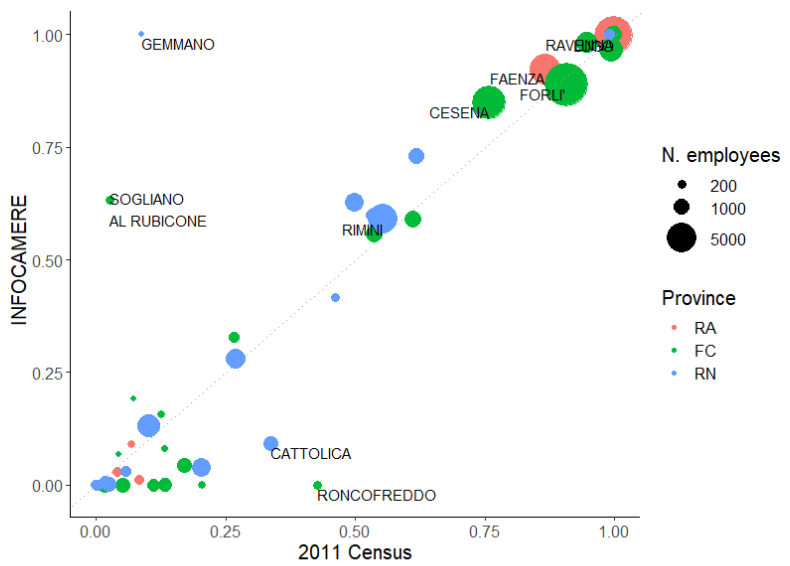
Figure 6: Synthetic indicator of exposure to floods




*Note:* This chart reports the synthetic indicator of exposure in equation (3) at the municipality level. The indicator ranges between 0 (no risk) and 3 (all employees work in flood-prone areas). The left panel reports the values of indicators by municipality. The right panel shows the distribution of municipalities' exposure by province.

Figure 7 shows that the share of employees exposed to non-zero flood hazards (indicator 2) computed with Census(x-axis) and InfoCamere (y-axis) data is similar in many municipalities. However, we observe a few cities for which Census data significantly underestimate (Sogliano sul Rubicone, Gemmano) or overestimate (Cattolica, Roncofreddo) the number of employees exposed to flood risk. We investigated the determinants of the difference in measuring exposure to flood risk for some municipalities. In particular, the high percentage of employees at risk in Roncofreddo, as evaluated in the Census datasets, is due to the assumption of uniform distribution of employees within census blocks, as most of the land surface in this municipality is exposed to flood risk. However, all of its manufacturing sites are located in a no-risk area, which is correctly captured by indicator (2).

Figure 7: Comparison with Census data




*Note:* This chart displays the relation between the share of employees in areas at flood risk according to our estimates (y-axis) and based on 2011 Census (x-axis).

### *3.2 Company-level indicators*

The main strength of our approach is in measuring the extent of the exposure to physical risks for each company. As described in Section 2.1, larger firms have multiple establishments, and measuring each site's exposure and relevance allows us to estimate a more reliable exposure index than those based solely on the geolocation of the headquarters.

We propose two indicators similar to those introduced in the previous section. The first index is the share of employees of company $i$ exposed to a given (but not higher - see Section 2.3) hazard level $S_k^i$:

$$S_k^i = \frac{\sum_{j \in \Theta(i)} W_{j,i} \mathbf{I}(\text{Hazard level} = k)}{\sum_{j \in \Theta(i)} W_{j,i}} \tag{4}$$

where $W_{j,i}$ is the estimated number of employees of firm $i$ in site $j$ and $\Theta(i)$ is the set of all establishments of firm $i$. For companies, the share of employees exposed to flood risk is more informative than the absolute number, as we do for geographical entities. This indicator can also be computed disregarding the difference in hazard levels to obtain an overall indicator $S^i$:

$$S^i = \frac{\sum_{j \in \Theta(i)} W_{j,i} \mathbf{I}(\text{Hazard level} \neq n)}{\sum_{j \in \Theta(i)} W_{j,i}} \tag{5}$$

As an example, Figure A3 shows indicators 4 and 5 for 3 different companies. These indicators allow a quick interpretation of the risk profile of each company, with Company

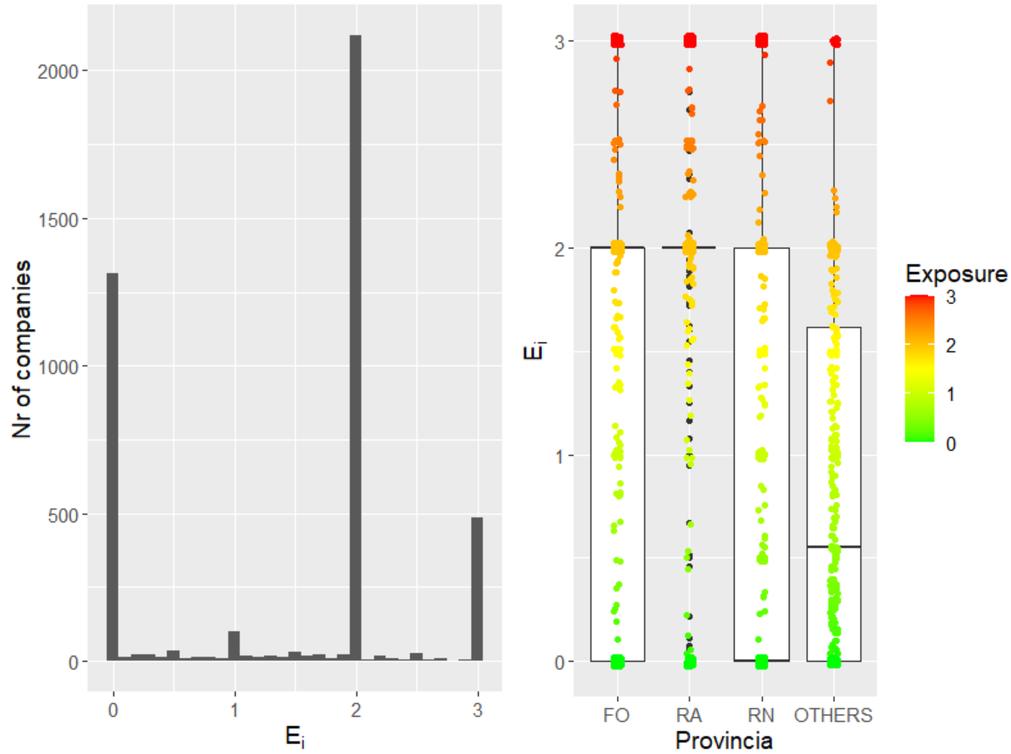
1 having more than 50% of workers exposed to some level of hazard (mostly medium level), Company 2 having the total of its employees exposed to the medium level hazard and Company 3 with a minority of workers ($\sim$ 15%) exposed to various hazard levels. We find that about 70% of companies in our sample are potentially exposed to floods, although to a different extent. Moreover, 7% of companies – accounting for 56% of employees – have only partial exposure to flood risk, i.e., $S^i$ larger than 0 and smaller than 1.

The third index, instead, is a synthetic indicator of the overall Exposure of company $i$ to flood risk:

$$E_i = \sum_{k \in \{n,l,m,h\}} S^i_k * f(k) \tag{6}$$

where, as before, $S^i_k$ is the share of employees exposed to hazard level $k$ but not to higher hazard levels and $f(\cdot)$ is defined as in the previous section.

Figure 8: Synthetic indicator of the exposure to floods for companies




*Note:* This chart reports the synthetic indicator of company exposure in equation (6). The indicator ranges between 0 (no risk) and 3 (all employees work in flood-prone areas). The left panel reports the distribution of the indicator. The right panel shows the distribution of companies exposure by the province of the headquarters.

Figure 8 shows the distribution of the indicator in (6) for all firms (left plot). The chart shows that values tend to concentrate on the integer values along the $x$ axis. This is explained by the fact that 70% of companies do not have branch offices and the riskiness is based only on the location of the headquarters. The share of companies with an Exposure index above two is higher in the provinces of Ravenna (>25%) and Forlì-Cesena (>50%), while the majority of the companies in the rest of our sample (Rimini and all other Italian provinces) has an Exposure lower than 1.

Interestingly, if we look at the Exposure values for companies headquartered in the centre of Milan (at low flood hazard) with premises in Romagna A4b, we notice that the Exposure indicator at the company level varies greatly: adding information on the exact position of secondary units allows a more precise evaluation of the real risk to which a company is exposed, and in situations in which headquarters are located in low-risk areas, this usually leads to an increased risk. In a more peripheral area (Faenza - Figure A4a), the risk level is correlated with local landscape morphology (risk decreasing with altitude), because companies tend to have less (if any) local units in the vicinity of the headquarters, thus maintaining the local hazard level.

It is essential to discuss the interpretation of these indicators. Natural hazards pose a risk to businesses because they can cause (*i*) damage to property and capital assets and (*ii*) business interruption. Unfortunately, we do not know whether a company owns or leases the buildings, and we do not observe the value of capital assets within a site. Therefore, it is difficult to estimate potential damage from the data available to us alone. Our exposure indicators are better suited to evaluate the possible loss of revenue due to disruption of production activities, assuming that the distribution of employees is a good proxy of an establishment's relevance for a company's overall activity.

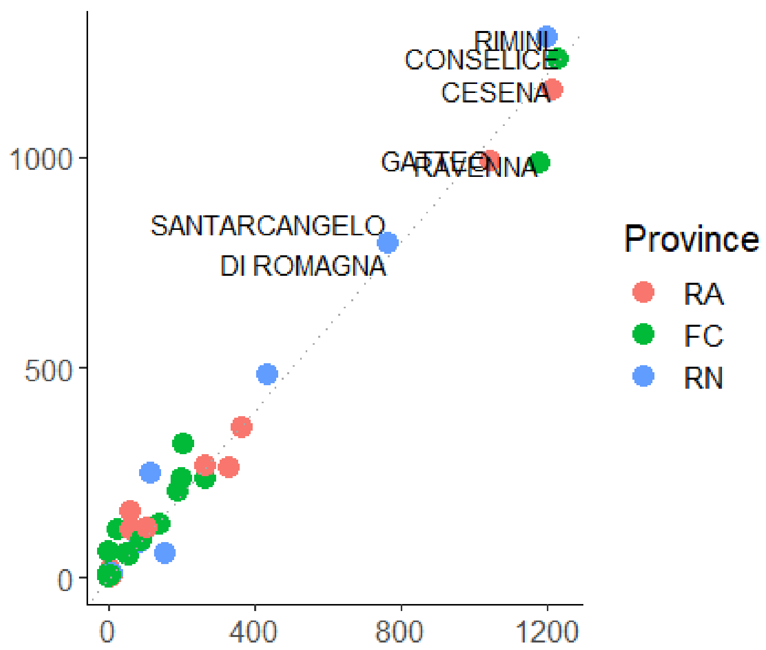
### *3.3 Accounting for branch offices matters*

How relevant is accounting for branch offices when assessing companies' exposure to flood risk? Motivated by data availability, a firm's exposure is usually quantified based on the headquarters' location. In 2023, for example, the ECB released the first set of analytical indicators on physical risks related to climate change. These indicators provide information on the risks for financial institutions related to their exposure to non-financial corporations in areas susceptible to natural hazards.[14] However, the location of the companies is based on RIAD, which collects data at the level of the legal entity.

[14] Details about these indicators are available at: https://www.ecb.europa.eu/stats/ecb_statistics/sustainability-indicators/data/html/ecb.climate_indicators_physical_risks.en.html.

To assess the impact of this approximation, we will compare the results of our methodology with a naive method where (*i*) we drop all the information about the branch offices, (*ii*) we check the exposure to physical risks based exclusively on the location of the headquarters, and (*iii*) we assume that all employees work in the headquarters. The first implication of the naive methodology is that only the extensive margin matters, i.e., whether a company is exposed to a hazard or not. When considering the branch offices, instead, we can have partial exposure because some establishments are exposed and others are not. To provide a practical example, we compute the indicator in (4) for a high hazard level (return period between 20 and 50 years).[15] According to the naive methodology that ignores the branch offices, 512 companies in our sample are exposed to high flood probability ($S^i_h$=1), and 3,515 are not ($S^i_h$=0). Our methodology shows that 476 firms have an index $S^i_h$ equal to 1, 3501 firms have $S^i_h$ equal to 0 while for 180 companies $S^i_h$ is between 0 and 1. In particular, 122 companies are partially exposed to high flood hazard when considering branches, but they are not when considering only the headquarters. For 56 companies, the opposite is true, i.e., considering only the headquarters would overestimate the exposure to flood risk. Although the number of firms is small in absolute terms, these companies are large and account for about 30% of employees in our sample.

Figure 9: Accuracy of the indicators based on the headquarters only




*Note:* The chart displays the number of employees in areas with a high probability of flood, $N^i_h$, at the municipality level in Romagna as measured by considering only the headquarters (x-axis) or also branches (y-axis).

[15]For this exercise, we excluded a few companies without employees in the headquarters.

Considering the branch offices matters also at more aggregate level, although to a different extent. Figure 9 reports the indicator $N_h^i$ (total number of employees exposed to high flood hazard) for the two different methodologies. As can be seen, the measurement error is significant for small municipalities and is usually associated with an increased indicator value.

### *3.4 Evaluation of geolocalization errors*

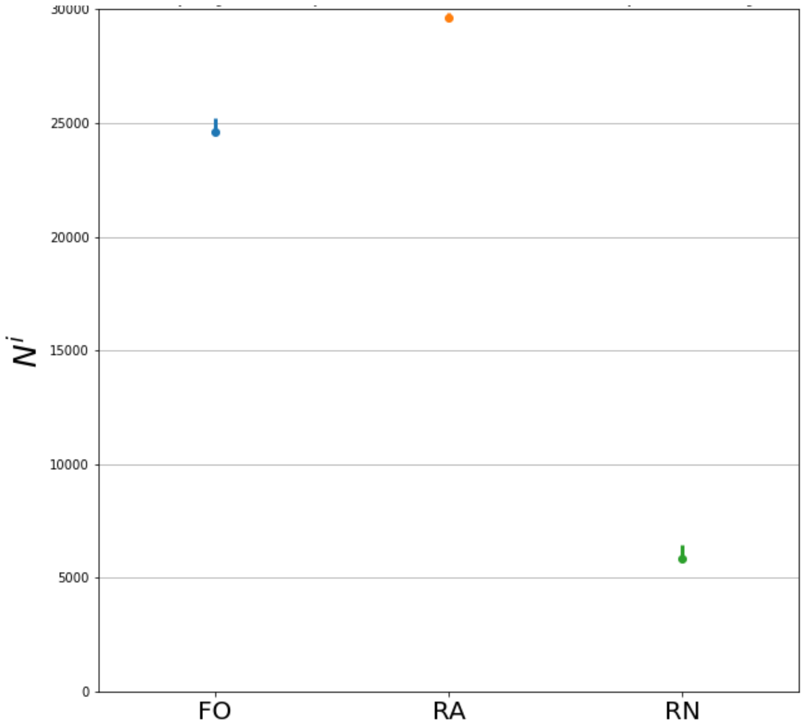
The geocoding services used in this study are affected by errors due to the imperfection of the map services they rely on. Table A5 shows the estimates of the different accuracy values for different services and quality criteria. We have chosen Google Maps for its superior accuracy. However, even Google Maps can fail to identify the coordinates of an address. For this reason, we provide a simple estimate of how the geocoding errors propagate in our results, which was performed via Monte Carlo techniques.

The process is based on artificially injecting errors in the data:

1. starting from Table A5, we estimate the probability distributions for the error terms in the longitude and latitude directions;
2. for each data point, we add to the longitude and latitude coordinates two random numbers extracted from these distributions;
3. we repeat the estimate of all exposure indicators.

This procedure is repeated, and an error is evaluated as the maximum deviation of the indicator values from the original one. Figure 10 shows the error estimates obtained with 10 repetitions of the MC procedure for indicator (2) at the province level. We see that the error is small, with a maximum deviation of +10% in the province of Rimini, +2.4% in Forlì-Cesena, and +0.06% in Ravenna, where most of the territory is exposed to some degree of flood hazard. However, it is important to consider that the geolocation error almost always leads to a slightly higher estimate of the $N^i$ indicator, which indicates that in some areas our estimates have to be considered as a lower bound to the true values.

Figure 10: A Monte Carlo assessment of the uncertainty about the location




*Note:* The chart reports the result of a Monte Carlo experiment on the indicator of the total number of employees in areas with non-zero probability of flood. The vertical lines represent the maximum deviation obtained after artificially introducing noise in the location of establishments and repeating 10 independent experiments.

## 4 The impact of flood in Emilia Romagna

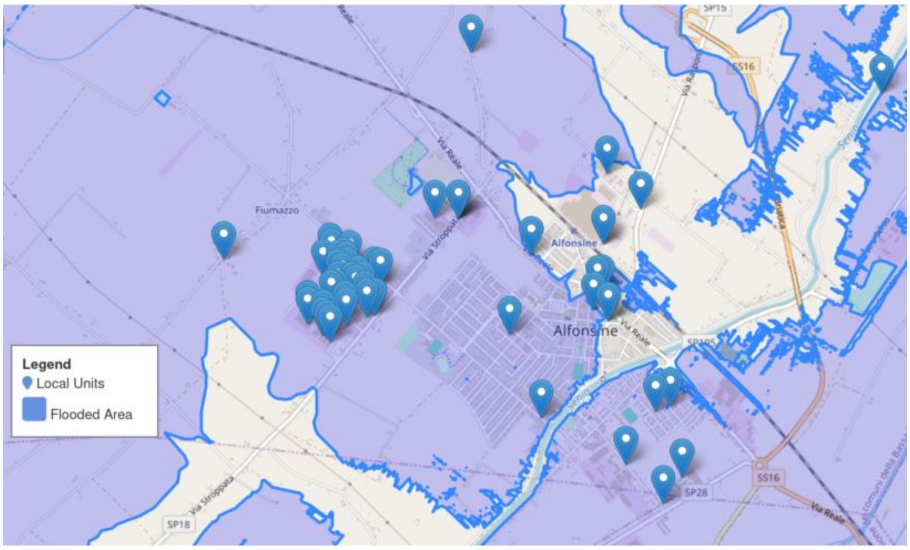
In May 2023, two floods hit Emilia Romagna. The first occurred on May 2-3. The second, causing more damage, occurred on May 16-17. The floods were caused by the heavy rainfall occurred over the first 21 days of May 2023 in that area, and a return time of $\sim 200$ years was estimated for such an extreme event (Barnes and others (2023)). In this section, we analyze the damage of the latter flood on companies operating in the provinces of Forlì, Ravenna, and Rimini.[16]

We focus on the mid-May flood because the Italian Civil Protection activated the CEMS's Risk and Recovery Mapping service. In mid-July, CEMS published a rich set of geospatial data that allows us to identify flooded companies accurately. These maps differ from those produced immediately after the onset of the flood (Rapid Mapping) because they rely on a larger and more heterogeneous set of data sources, including multiple satellite observations and on-site reports. The maps have been validated and show an overall >98% accuracy in detecting flooded areas. In addition, CEMS used a hydraulic model of the areas to better identify the flooded regions.

[16]The flood also affected part of the province of Bologna. However, we excluded Bologna because the sample of companies would have grown considerably.

This approach improves the accuracy of defining the flooded areas and provides precise water level estimates. To provide an example of why CEMS maps are helpful, Figure 11 shows the impact of the flood in Alfonsine, a small town in the province of Ravenna, where 80% of manufacturing firms were flooded. Thanks to CEMS maps, we can distinguish flooded firms from those that were not hit. Overall, the flood struck 1206 headquarters or branch offices in our dataset. Regarding employment, we estimate that these establishments employed about 18 thousand workers.

Figure 11: An example of CEMS flooded areas



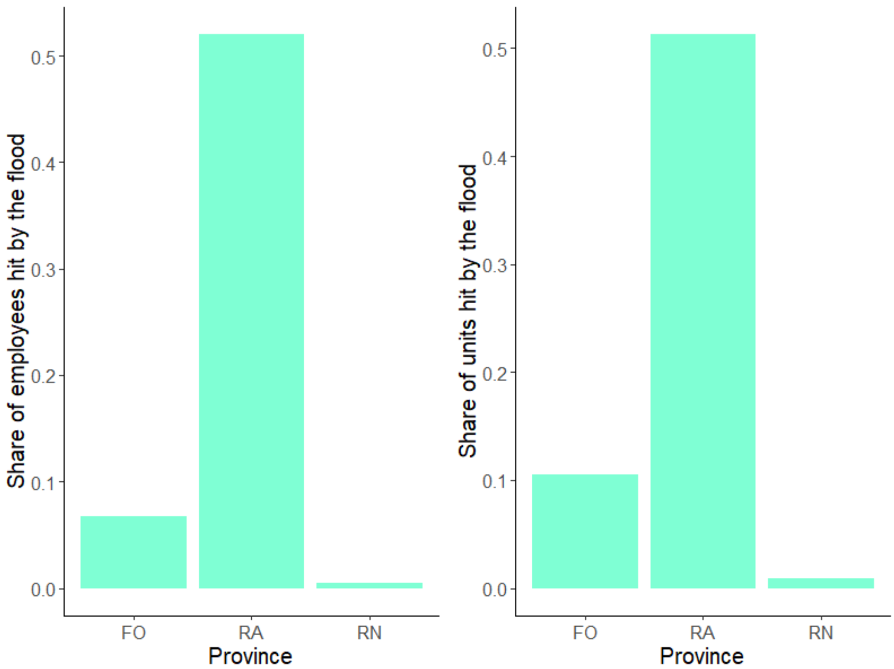

*Note:* The chart displays the map of the municipality of Alfonsine with the maximum water extent during the flood events and all the manufacturing establishments in the area.

The percentage of establishments and employees hit by the flood is shown in Figure 12. The flood hit about 50% of establishments in the province of Ravenna and only a tiny fraction of firms in the province of Rimini. Figure 13 shows the 11 municipalities in which the flooding hit more than half of the manufacturing sites.

Based on CEMS maps, we can also calculate the intensity of the flood for the establishments that have been hit. The median firm hit by the flood faced a 0.6-meter flood, but for the top 1% of the distribution, the flood level was higher than 2 meters (Figure 14).

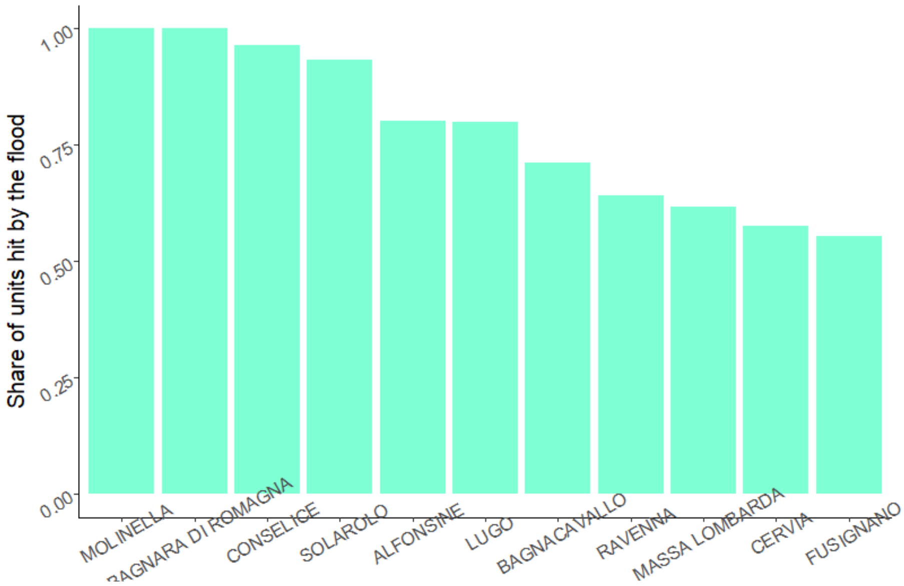
Finally, we want to assess the reliability of the ISPRA hazard maps we employed to develop our risk indicators. To do this, we concentrate on all establishments hit by the flood and check how they distribute among hazard levels. Most establishments were classified as exposed to moderate to high hazard levels, with a negligible minority (1.3%) considered at low or zero risk. This indicates a satisfactory risk assessment performance of these maps in our area of interest.

Figure 12: Shares of establishments and employees hit by the flood




*Note:* The chart shows the shares of manufacturing establishments and employees hit by the flood by province.

Figure 13: Municipalities most affected by the flood

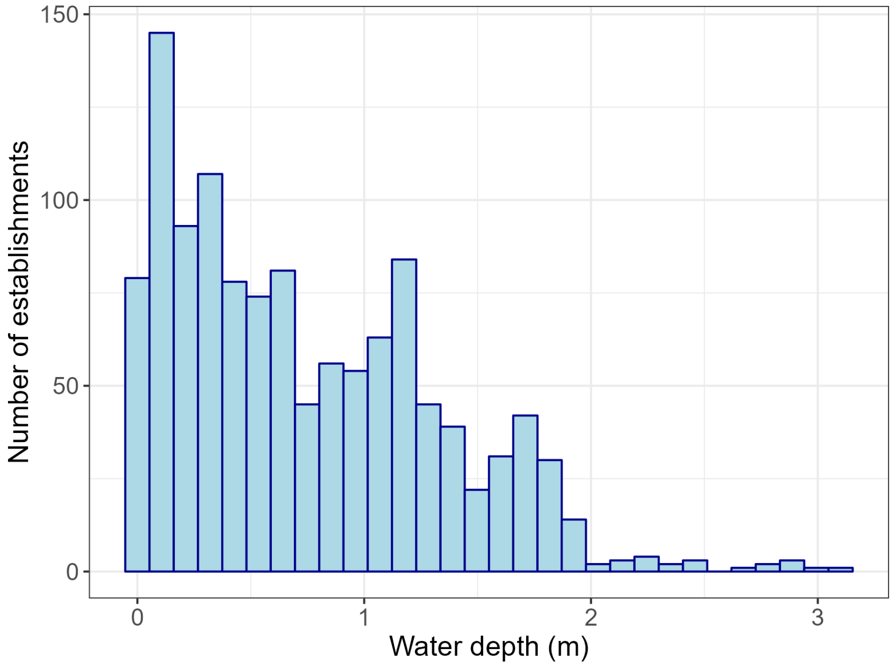



*Note:* The chart reports the share of manufacturing establishments hit by the flood in most affected municipalities.

We made the same analysis by exploiting the JRC river flood maps developed by Dottori et al. (2022), and the results were disappointing. According to the JRC maps, about 95% of flooded establishments were in a zero-risk area. In Alfonsine, for example, all flooded establishments were inside the ISPRA flooding zones. Instead, based on JRC maps only 1 out of 58 flooded establishments were exposed to food risk, indicating a potential underestimate of hazards. A similar conclusion is drawn in the work of Marchesini et al. (2021), where an innovative, data driven approach for estimating flood exposure is proposed and compared to ISPRA and JRC maps.

Overall, these results support our choice to select ISPRA hazard maps.

Figure 14: Maximum water depth experienced by establishments hit by the flood




*Note:* This chart displays the distribution of the maximum water depth level experienced by flooded establishments.

Finally, we discuss a further benefit of our methodology. By explicitly considering branch offices, we can identify all firms affected by a localized extreme event through their network of local branches. About 17% of the companies that have been flooded have their headquarters out of Romagna. For example, seven companies headquartered in Milan. This is important for two reasons. First, that shows how the effects of localized natural hazards go well beyond the area that has been hit. Second, looking only at headquarters provides a biased picture of the impact of natural hazards on business.

Summing up, the recent increased availability of satellite data and the development of sophisticated hydraulic models make it possible to identify flooded firms accurately and, in principle, estimate past floods' impacts. Moreover, the experience of the May 2023 flood suggests that ISPRA flood maps are reliable in Emilia Romagna.

## 5 Next steps

This paper investigates the potential to enhance the precision of determining companies' exposure to natural hazards by leveraging the location of their branch offices. This is an exploratory analysis, so the paper should be extended in several directions. In this section, we discuss the main caveats and priority research directions.

**Company data**. Our priority is to extend the analysis to all industrial companies. These firms are often located in rural areas; sometimes, because of the type of activities they carry out, they are located in areas of high hydrogeological risk. For example, some plants need to be close to rivers to have access to sufficient water for machinery cooling. We will later extend the analysis to market service enterprises.

A key issue is that we do not observe the number of employees by branch. This information is available only in the ASIA dataset (*Registro Statistico delle Imprese Attive*), but access to this dataset is restricted. In this respect, we plan to introduce a new procedure that exploits the information on the typology of branches (plant, warehouse, etc.) for companies having one establishment per municipality to provide a more accurate estimate of the employees.

A further improvement would be introducing other variables besides employees, such as turnover or value added, into the dataset. This information would be necessary for estimating the economic impact of extreme events. The CERVED database can be used for this purpose, but it reports the financial statements of only a portion of enterprises. Therefore, we should develop an imputation method of balance sheet variables for companies not in the CERVED dataset.

There are two additional data gaps. First, we have branch office data available from 2020. This prevents us from investigating the presence of adaptation strategies put in place by companies. The increased frequency of extreme events and increased awareness of the possible effects of climate change may have already affected firms' location choices. In particular, we expect a gradual decrease in new business locations in the more risky areas. Then, at present, we cannot answer this research question. However, in the future, the InfoCamere dataset may also incorporate local units for 2005-2020. Moreover, the dataset Orbis Historical reports information about branches, although the quality of the information must be assessed.

Second, we do not know if the company owns its buildings or if it is the lessee. This information is essential to estimate the potential damages from natural hazards better. The only source for deriving this information is the cadastral register, which reports the owner of each property. However, access to the cadastral registry in Italy is restricted, which prevents extensive data extraction. Therefore, bridging this data gap will require interaction with the tax office (*Agenzia delle Entrate*).

**Geocoding**. Geolocation accuracy is very high on average, but we could improve it for some establishments using more sophisticated tools. For example, Google Places is a service that provides geolocation of an establishment (if the establishment is on Google Maps) from the name of the business, even if the address is inaccurate. However, Google Places is more expensive than Google Maps API. Therefore, an optimal strategy might be to use Google Places only when the quality of geolocation is low.

We will also evaluate the quality of ArcGIS-ESRI service for georeferencing versus using Google Maps. Indeed, using Google Maps services is subject to significant contractual restrictions and difficulties in acquiring services because Google (as well as TomTom) is not compliant with Italian public procurement regulations.[17] ArcGIS-ESRI is a service that combines maps from different providers (including TomTom) and is provided by an Italian company that already works with public administrations.

Finally, geocoding services provide a single point for each address. For some applications, however, knowing the area covered by the establishments would be important. The establishment's area may be recovered through land cover data and OpenStreetMap.

**Hazards**. Gathering information about natural hazards will be a difficult task. Currently, there are many more resources available than in the past. However, the quality and accuracy of these resources are sometimes questionable, leading to the risk of attributing a very biased measure of exposure to a company.

We plan to investigate the availability of risk maps for different natural hazards at Italian research institutes, such as ISPRA, Istituto di Ricerca Idrogeologica (CNR-Irpi), and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC). As with the flood risk case described in section 3, maps from international research institutes, such as the JRC, may not be entirely reliable in the Italian case because they need to adopt harmonized criteria to facilitate comparability to all countries. Thus, the strategy is to identify national geospatial databases that are more accurate than harmonized European databases for assessing companies' exposure to nat-

[17] We currently use personal accounts that allow free georeferencing of up to 40 thousand addresses per month.

ural hazards. For example, CNR-Irpi developed a new set of flood maps based on a harmonized methodology for all Italian regions (Marchesini et al., 2021), and CMCC produces a granular climate risk index accounting for projections about climate trends (Mysiak et al., 2018). However, the JRC datasets would still be used to obtain comparable statistics with other countries and the institutions that use them, such as the ECB.

Flood risk analysis presents an additional difficulty because European regulations require the definition of official risk maps. In Italy, these are the ISPRA maps. On the one hand, ISPRA maps should be preferred to other maps because ISPRA maps are a benchmark and have real effects, for example on urban planning regulations. On the other hand, ISPRA maps have important drawbacks. For some regions, using other maps could be preferable. Therefore, there is a trade-off that is not easy to solve.

**Past events**. Data on past events are crucial to predict the impact of future events on companies. Indeed, a key issue for quantifying risk is that we do not have reliable estimates of the vulnerability of companies to natural hazards, i.e., conditional on the realization of an event, which is the expected loss for companies in terms of assets and turnover. Regarding this aspect, we should proceed in two directions. First, we must explore some repositories of past natural disasters. The JRC Risk Hub collects several resources on past events in Europe. MODIS reports wildfires burned areas since 2002. CEMS covered the most relevant disasters in the last decade. ESWD is a large dataset reporting a comprehensive list of extreme weather events at the municipality level. Second, we should merge the information about the exposure to past events with financial statement data to estimate the impacts of these events on company activity. Our main limitation is that branch office data has been available in InfoCamere only since 2020. Therefore, we can focus on a small set of events. The most interesting case study is the May 2023 flood in Emilia Romagna. However, to study the impacts of this episode, we must wait until financial statements for 2023 are available.

A further goal is to define criteria for exploiting the CEMS Rapid Mapping service maps. As discussed in the Appendix, the CEMS Rapid Mapping service makes it possible to estimate the damage of a natural disaster within days of the event. Given this rapidity, the accuracy of the maps is lower than those produced by the Risk and Recovery mapping service. In particular, Rapid Mapping may underestimate the areas affected by the natural disaster. For this reason, in the case of the November flooding in Tuscany, Giordano and Russo (2023) consider all businesses within a 100-meter radius of the flooded areas as inundated. In contrast, in the case of the May flooding in Emilia Romagna, Banca d'Italia (2023) considers all headquarters within a one-kilometer radius as flooded. In the future, we plan to estimate the margin of error of Rapid Mapping by exploiting the event in Emilia Romagna, for which both Rapid Mapping and Risk and Recovery Mapping services have been activated.

The above discussion concerns estimating the direct damage of extreme events on companies. However, extreme events can also have indirect effects on businesses. For example, in the case of a flood, a company may not have suffered damage to its plants but is forced to stop its operations because of damage to infrastructures (e.g., roads and railways). Therefore, we should develop a methodology to identify enterprises indirectly affected by an extreme event. To this end, using network techniques, we could potentially use OpenStreetMap to identify road infrastructures affected by an extreme event and assess their relevance to mobility.

## 6 Conclusions

This paper proposes a new methodology for assessing Italian companies' exposure to natural hazards that accounts for the distribution of companies' activity across different sites and locations. We apply this methodology to evaluate the exposure to flood events for a sample of manufacturing companies holding establishments in three Italian provinces. Accounting for branch offices significantly affects the quantification of flood exposure, particularly for large firms, causing significant shifts in effective hazard for companies holding headquarters in low-risk areas, e.g. Milan.

Moreover, we exploit flood maps developed by CEMS for emergency and recovery management to assess the impact of a large flood in Emilia Romagna in May 2023. We show how to use CEMS data to identify flooded companies and proxy for the intensity of the shock at the company level.

We remark that the results we presented are still preliminary, and we know the limitations we should overcome. However, we think this paper makes important contributions to analyzing climate risks to Italian companies. First, we propose a workflow for the proper measurement of physical risks. Second, we survey the available data, the limitations of the data used in this analysis, and possible solutions to improve the measurement of risks. Third, we identify data sources for future analysis of damages from climate-related hazards. In the medium term, our proposed strategy will significantly improve the assessments of physical risks for Italian companies.

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# Appendix

## A Supplementary figures and tables

Table A1: Composition of the sample by NACE-2 sector

| NACE-2 | Description | Total |
|---|---|---|
| 25 | Metal products | 851 |
| 10 | Food industry | 480 |
| 28 | Non-metal mineral processing | 373 |
| 33 | Machinery maintenance and installation | 271 |
| 31 | Furniture production | 241 |
| Others | - | 1941 |

*Note:* The table reports the number of firms in the top five sectors by NACE-2 digit code.

Table A2: Summary statistics

| | Companies | Branch Offices | Employees | Employees in branches | Employees in AOI |
|---|---|---|---|---|---|
| HQ inside AOI | 3878 | 1690 | 78776 | 29530 | 74034 |
| HQ outside AOI | 279 | 2736 | 61419 | 51509 | 8325 |
| Total | 4157 | 4426 | 140195 | 81039 | 82359 |

*Note:* The table reports the summary statistics about the number of companies, branch offices, and employees. The breakdown is based on the headquarters (HQ) location. The area of interest (AOI) are the provinces of Forlì, Ravenna, and Rimini.

Table A3: Composition of the sample by employees and age

*Panel A: Distribution of companies by employees*

| | 1-5 | 5-20 | 20-50 | 50-250 | 250-500 | 500+ | |
|---|---|---|---|---|---|---|---|
| Total | 1752 | 1578 | 449 | 290 | 48 | 40 | 4157 |
| FC | 683 | 675 | 185 | 100 | 10 | 3 | 1656 |
| RA | 542 | 452 | 146 | 79 | 11 | 9 | 1239 |
| RN | 521 | 430 | 94 | 61 | 7 | 2 | 1115 |
| Other provinces | 6 | 21 | 24 | 50 | 20 | 26 | 147 |

*Panel B: Distribution of companies by age*

| | 0-10 | 10-20 | 20-50 | 50+ | |
|---|---|---|---|---|---|
| Total | 832 | 847 | 2116 | 230 | 4025* |
| FC | 316 | 306 | 882 | 97 | 1601 |
| RA | 255 | 270 | 600 | 78 | 1203 |
| RN | 237 | 231 | 569 | 38 | 1075 |
| Other provinces | 24 | 40 | 65 | 17 | 146 |

*Note:* The table shows the distribution of companies by employees and age and the breakdown by province. Panel A reports the distribution of companies by the number of employees, while Panel B shows the distribution of companies by age (measured in years). * *132 companies miss age information*

Table A4: Classification of secondary units

| Type of unit | Total |
|---|---|
| Stores | 1,373 |
| Deposit | 796 |
| Factory | 526 |
| Office | 240 |
| Laboratory | 210 |
| Others | 1,281 |

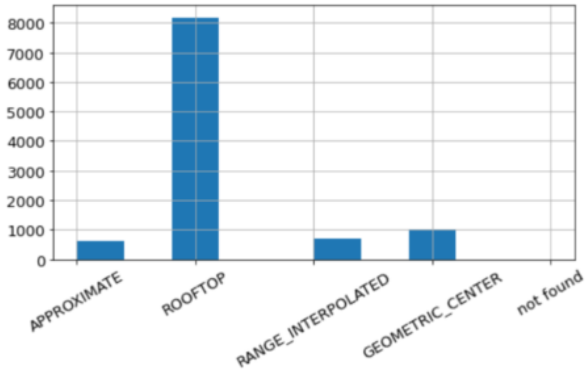
*Note:* The table reports how the secondary units in our study are classified

Table A5: Accuracy of different geocoding services

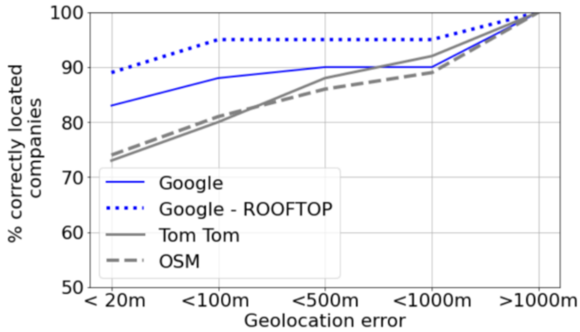
| Radius | OSM | TomTom | Google Maps |
|---|---|---|---|
| 20m | 75% | 74% | 83% |
| 100m | 82% | 81% | 88% |
| 500m | 87% | 89% | 89% |
| 1000m | 90% | 93% | 89% |

*Note:* The table shows statistics on the accuracy of different geocoding services based on a sample of 100 randomly chosen addresses for which we know the correct location. Each row displays the percentage of addresses geocoded within a given radius of the correct location.

Figure A1: Summary statistics on Google Maps precision compared to other services




(a) Quality of Google Maps geocoding




(b) Comparison between geocoding services

*Note:* The chart displays statistics on the accuracy of different geocoding services based on a sample of 100 randomly chosen addresses for which we know the correct location. Panel (a) reports statistics about the geocoding quality according to Google Maps. Google Maps reports four possible levels of precision: *rooftop* means that the exact address is matched; *range interpolated* and *geometric center* indicate that the result refers to either the centroid of the street or a bounded area (i.e., *zona industriale* or *contrada*) possibly because the street number is missing; *approximate* indicates that the precision of the result is possibly low. Panel (b) displays the precision for different services. For Google Maps, we report the average precision and the precision conditional on being classified as *rooftop*.

Table A6: Comparison of Google Maps and OSM

| Quality | Emilia Romagna | | | Other regions | | |
|---|---|---|---|---|---|---|
| | N | Freq. | Distance | N | Freq. | Distance |
| 1 | 236 | 0.04 | 2107.3 | 565 | 0.17 | 2453.1 |
| 2 | 495 | 0.08 | 150.1 | 1182 | 0.37 | 231.8 |
| 3 | 5541 | 0.88 | 29.3 | 1488 | 0.46 | 89.9 |

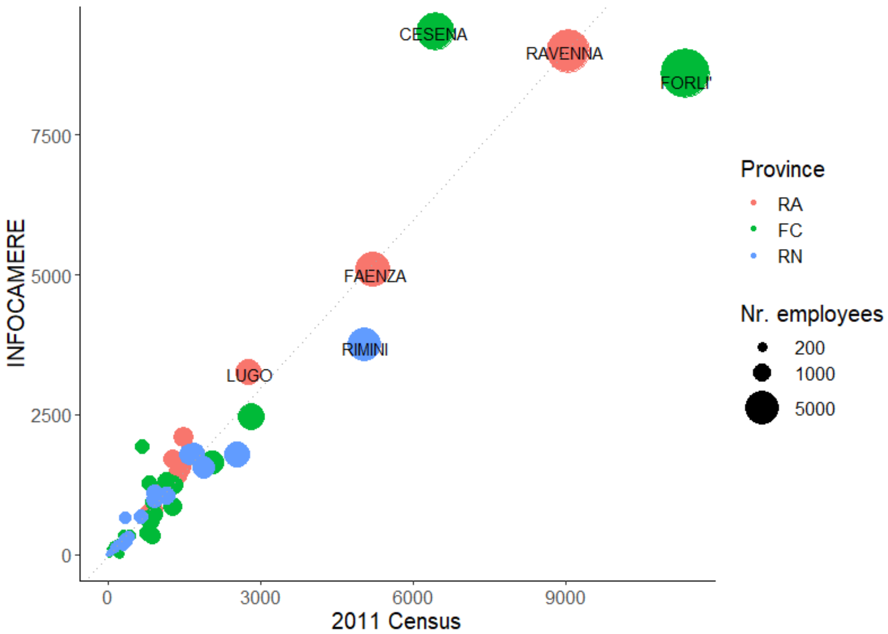
*Note:* The table reports the average distance of geocoded address between Google Maps and OSM for the following levels of quality of the OSM geolocation: 1: we matched only the municipality; 2: we matched the municipality and the street name; 3: we matched the whole address. The statistics are computed separately for the Emilia Romagna and other regions.

Table A7: Companies location and land cover

| Land cover | N | Frequency | Cumulative frequency |
|---|---|---|---|
| Manufacturing settlements | 3243 | 53.7 | 53.7 |
| Sparse residential settlements | 1061 | 17.6 | 71.3 |
| Road network | 814 | 13.5 | 84.7 |
| Urban residential area | 393 | 6.5 | 91.3 |
| Commercial settlements | 230 | 3.8 | 95.1 |

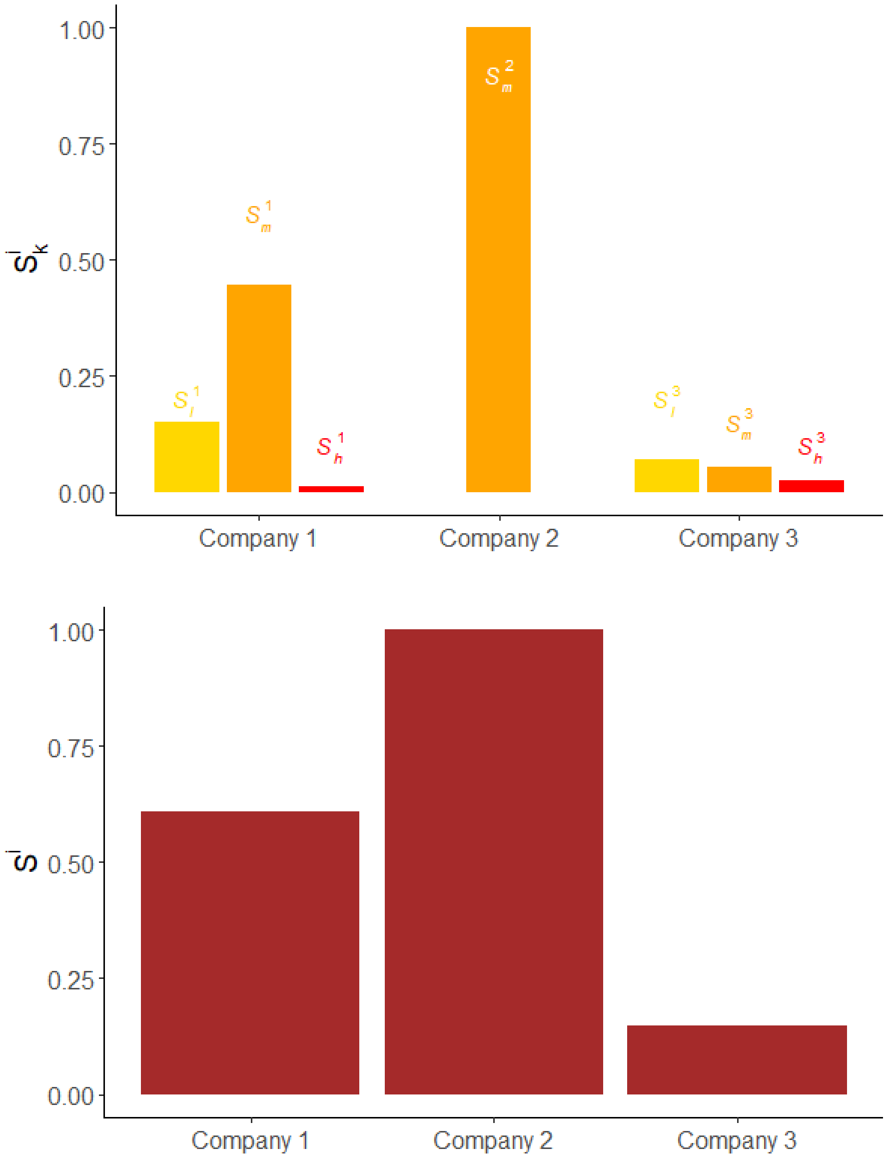
*Note:* The table shows the distribution of companies across different types of settlements. We extrapolate the land use corresponding to the location of each firm from the official land cover map for Emilia Romagna.

Figure A2: Comparison between employment in our dataset and the 2011 Census



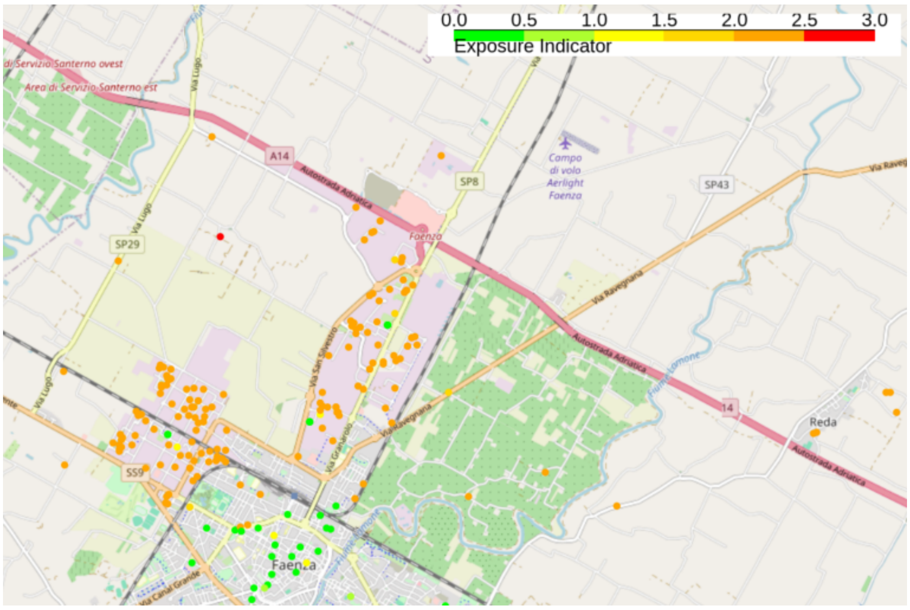

*Note:* The chart displays the comparison between the number of employees in the manufacturing sector for the municipalities in Romagna according to our estimates based on Infocamere (y-axis) and the 2011 Census (x-axis).

Figure A3: Companies exposure to floods. An example

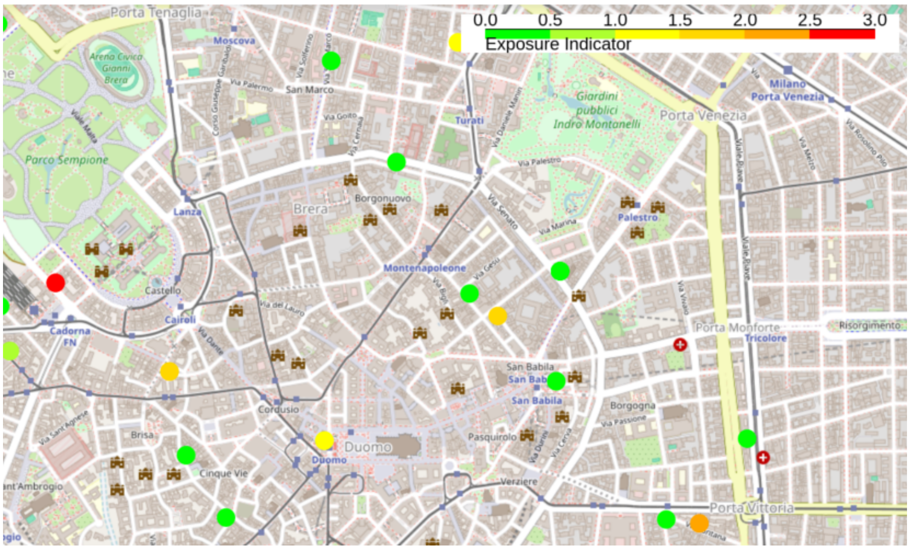



*Note:* The chart reports the indicators of exposure to flood hazard for a sample of three companies operating in Romagna. The three companies are... The upper plot displays the share of employees by hazard level in equation (4). The bottom plot shows the cumulative share of employees exposed to floods in equation (5).

Figure A4: Exposure to flood hazard in Faenza and Milan




(a) Faenza




(b) Milano

*Note:* The chart displays the synthetic indicator of exposure for companies with headquarters in Faenza and Milan. Each dot is the headquarters of a company.

## B Copernicus and its Emergency Management System

The primary purpose of the Copernicus project is to provide accurate, timely, and reliable information about the Earth's environment, land, oceans, and atmosphere. This is achieved through a network of satellites, ground-based, airborne, and seaborne sensors, as well as data and information processing facilities.
Copernicus serves various authorities and stakeholders, including the European Spacial Agency and the European Commission, which is also its main funding authority.
One of the main components of the Copernicus Project is a series of satellites called Sentinel, equipped with various sensors and instruments designed to capture data across multiple wavelengths and for various purposes. The Sentinel 1 satellite uses Radar imaging and is particularly useful for flood detection, not only because it can detect water coverage but also for being unaffected by the presence of clouds above the area of interest. Unfortunately, one of its antennas was lost in 2021, meaning that data acquisition for a specific location occurs at a lower frequency.
Besides providing satellite imagery, Copernicus offers a range of services focusing on specific tasks, e.g. air quality or atmosphere monitoring. Among these, the Copernicus Emergency Management System supports emergency and crisis management activities by providing timely and accurate geospatial information. It offers access to a wide range of satellite imagery and geospatial data to monitor and assess emergency situations, including floods, wildfires, earthquakes, tsunamis, volcanic eruptions, and other disasters. The service does not operate continuously, usually being activated by national authorities upon the occurrence of emergencies (e.g., floods, wildfires). The service can provide two types of products:

- Rapid Mapping provides geospatial information within hours or days of a service request in order to support emergency management activities in the immediate aftermath of a disaster
- Risk & Recovery Mapping supplies geospatial information in support of Disaster Management activities including prevention, preparedness, risk reduction and recovery phases

The main differences between the two products regard timeliness and accuracy: Rapid Mapping provides information within hours, however quality assessment is limited and products can undergo several updates after the first release. Risk & Recovery mapping is available weeks/month after the emergency, but undergoes a full quality evaluation process and usually assures very high accuracy levels.