Assessing the effectiveness and the economic impact of evacuation: the case of Vulcano Island, Italy

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Abstract

Evacuation planning and management represents a key aspect of volcanic crises because it can increase ~~people~~people's protection as well as minimize ~~the~~ potential ~~impact~~impacts on the economy, properties, and infrastructure of the affected area. ~~Assessment of evacuation scenarios that consider human and economic impact is best done in a pre-disaster context as it helps authorities develop evacuation plans and make informed decisions outside the highly stressful time period that characterizes crises.~~ We present an agent-based simulation tool that assesses the effectiveness of different evacuation scenarios using the small island of Vulcano ~~island ((south~~ Italy) as a case study. Simulation results show that the overall time needed to evacuate people should be analysed together with the percentage of people evacuated as a function of time and that a simultaneous evacuation on Vulcano is more efficient than a staged evacuation. For example, during the touristic (high) season between July and August, even though the overall duration is similar for both evacuation strategies, after ~6 hours about 96% of people would be evacuated with a simultaneous evacuation; in contrast, only 86% would be evacuated with a staged evacuation. We also present a model to assess the economic impact of evacuation as a function of evacuation duration and starting period ~~that~~with respect to touristic season. It reveals that if an evacuation ~~of Vulcano would cause significant economic impact to the tourism industry if~~ lasting ~~more than~~ 3 to 6 months ~~(in case it~~ was initiated at the beginning ~~of the visitor season) to 1 year (in case it was initiated~~or at the end of the ~~visitor season).~~ touristic season (i.e., June or November), it would cause a very different economic impact to the tourism industry (about 78-88% and 2-7% of the total annual turnover, respectively). Our results show how the assessment of evacuation scenarios that consider

human and economic impact carried out in a pre-disaster context helps authorities develop evacuation plans and make informed decisions outside the highly stressful time period that characterizes crises.

Keywords: volcanic crisis, emergency evacuation, evacuation modelling, staged evacuation, simultaneous evacuation, evacuation effectiveness, La Fossa volcano

1. Introduction

Evacuation is a key measure used in emergencies that can save lives and reduce human impact (e.g~.~., Moriarty et al., 2007; Tomsen et al., 2014; Thompson et al., 2017). The call for evacuation is often taken under periods of pressure and uncertainty (Bebbington and Zitikis, 2016) and is often a costly decision ~~which, depending on how it is managed,~~that can lead to both positive and negative outcomes, depending on how it is managed (Doyle et al., 2014). Miscalculation or delays in the key phases of the evacuation process such as, for example, the timing when the evacuation order is issued, the channels and sources through which the order is communicated to the public, the time required by the population to process and implement the evacuation order ~~and their actions~~, and evacuation logistics and routes, can significantly reduce the evacuation effectiveness (Sparks, 2003; Sorensen and Sorensen, 2007; Lindell et al., 2019). Evacuation planning carried out in a pre-disaster context provides a better understanding of when to issue evacuation orders, who should be evacuated at what time, which routes and alternate routes should be considered, where evacuees should go, what resources are needed and how long the evacuation might last (MCDEM 2008; Marzocchi and Woo, 2009). In this regard, volcanic crises differ from many other natural hazards as they are often associated with an *unrest* phase, during which most volcanic systems exhibit precursors from hours to days, weeks, and even months before the onset of an eruption (Gregg et al., 2015). ~~These~~The unrest ~~phases are~~phase is typically associated with long-lasting, time-dependent uncertainties regarding forecasts on where, when, and even if a future eruption will take place. However, ~~volcanic unrest~~it also represents an important ~~phase~~opportunity during which preparedness activities can, and should, be initiated with the aim of increasing resilience of the system as well as facilitating the potential evacuation.

Evacuation orders can be issued before the actual onset of an eruption ~~onset in case~~when increasing volcanic unrest is observed. This type of evacuation is an important preventive measure and an efficient response to minimize human impacts (~~Wilson et al., 2012;~~Baxter et al., 1998; Leone et al., 2019; Wilson et al., 2012). If planned and implemented well, preventive evacuation can save lives as was the case in many past volcanic emergencies, including the 1991 eruption of Pinatubo volcano in the Philippines, the 2006 and 2010 Merapi eruption in Indonesia, the 2017-2019 eruption of Mt. Agung in Bali and the 2017-2018 eruption of Manaro Voui in Vanuatu~~.~~ (e.g., Leone et al., 2019). Evacuation can also be initiated after the beginning of an eruption, especially in the case of short-~~or~~fuse events with little to no warning. In these situations, people may have to be evacuated due to the approaching of potentially impactful hazards such as lava flows, pyroclastic density currents (PDCs), lahars and tephra fall~~.~~ (e.g.,

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2021 eruption of Cumbre Vieja, La Palma, Spain; https://volcano.si.edu/volcano.cfm?vn=383010#September2021). However, failure to evacuate in anticipation of an eruption or of the associated primary and secondary hazards can lead to catastrophic outcomes as seen during the 1985 Nevado Del Ruiz eruption in Colombia and during the 2018 Fuego eruption in Guatemala (Voight et al., 2013; IFRCb 2019; Leone et al., 2019).

Unlike other emergencies, the duration of volcano-related evacuations can last for days, months or even years depending on the ~~type~~style of eruption and its impacts on the landscape and can result in long-lasting or even permanent relocation of communities (e.g., Soufrière Hills, Montserrat and Tungurahua, Ecuador; Barclay et al., 2019). ~~In detail,~~Evacuations involving long ~~duration of evacuation occurs~~durations mostly occur because ~~i)~~periods of elevated unrest ~~can be protracted, ii)~~or eruptive

		Tangible Costs	Intangible (non-market) Costs
Damage Costs	Direct	Physical damage to assets: e.g. buildings, infrastructure	Loss of life Health effects Loss of environmental goods
	Business Interruption	Production interruption because of destroyed machinery	Ecosystem services interrupted
	Indirect	Induced production losses of suppliers and customers of companies directly affected by the hazard	Inconvenience of post-hazard recovery Increased vulnerability of survivors
Risk Mitigation Costs	Direct	Set-up of mitigation infrastructures Operation and maintenance costs of those infrastructures	Environmental damage due to the development of mitigation infrastructure or due to a change in agricultural practices
	Indirect	Induced costs in other sectors due to the disruption caused by the mitigation measures	Impact on the well-being due to the disruption of services

Table 1 Cost categorizations with examples (modified from Meyer et al, 2013)

activity can be protracted, ~~iii)~~ post-eruption activity such as remobilisation of pyroclastic deposits by water (i.e., lahars) and wind (i.e., ash storms) can continue threatening communities, and/or ~~iv)~~ the damage can be so overwhelming that people and their government lack the resources to rebuild in a timely period.

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90   While evacuations can save lives, they are often costly and may trigger other adverse economic and social impacts (e.g., Woo, 2008; Bouwer et al., 2011), especially in the context of false alarms (e.g. Woo, 2008). Additionally, the consequences of a certain hazardous phenomenon can be lower than predicted. As an example, since the 1950s, 75% of evacuations issued due to tsunami warnings turned out to be either false alarmsnon-events or the tsunami generated tsunami was not as impactful as

95   expectedanticipated (The Economist 2003; Selva et al., 2021). In this context, the potential economic impacts of an eruption should be accounted for in the process of decision-making for evacuations. According to Meyer et al. (2013), the management of natural risks can result in five different types of

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costs (**Table 1**). First, direct costs that result from the physical destruction of assets due to the interaction with hazards. Second, business interruption costs that refer to losses that occur in areas directly affected

100 by the hazard when people are not able to carry out their work because the workplace is destroyed, damaged or not accessible.inaccessible. Third, indirect costs that are induced by either direct damages or business interruption costs (e.g., production losses for suppliers and customers of entreprises); they can occur inside or outside of the hazard zone. Fourth, intangible costs that concern damages to goods and services for which market prices do not exist, such as the impacts on environment, health or cultural

105 heritage. Fifth, risk mitigation costs, which include risk management planning and adaptation plans, hazard modification, monitoring and early warning, emergency response and evacuation. This category itself can also be divided in subgroups of costs such as direct (any action taken for mitigation infrastructures), indirect (secondary costs such as economic disruption due to mitigation measures) and intangible (e.g., environmental damage due to change in agriculture practices) costs (Meyer et al.,

110 2013). In this study, we are mostly concerned with the third type of cost related to the interruption of economic activities (i.e., tourism) as a result of a prolonged evacuation.

In this context, weWe present here a novel methodology to couple an evacuation model with an assessment of its potential economic impact. We use the island of Vulcano, in the Aeolian Islands of

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south Italy~~,~~ to illustrate strategies for the assessment of the effectiveness of an evacuation as well as ~~its~~ the associated economic impact on the island's main source of revenue~~, i.e. tourism. In the past decade, evacuation and civil protection planning have been underway in Italy for the main active volcanoes (e.g. Vesuvius and Campi Flegrei, www.protezionecivile.gov.it; Baxter et al., 2008; Marzocchi and Woo, 2009). However, with the exception of Stromboli Island after the volcanic-induced tsunami in 2002, limited planning efforts have been carried out for the other volcanic systems in the Aeolian Islands, an archipelago in the South~~ during periods of ~~Italy composed of seven islands. The Aeolian islands, which earned UNESCO World Heritage status in 2000, are a volcanic arc associated with the subduction of the African plate under the Eurasian plate, of which Stromboli volcano~~varying population on the island ~~of Stromboli and La Fossa volcano on the island of~~. On Vulcano ~~are the youngest and most active volcanic edifices (Selva et al., 2020).~~

, the low touristic season (i.e., when fewer visitors are on island) occurs during the months of November-March, while the high season is in July-August. We developed an ~~agent~~Agent-based ~~simulation~~modelling (ABM) in GIS space using the AnyLogic® software platform to assist emergency managers and assess the effectiveness of specific evacuation parameters, i.e. number of people present on the island (during the low and high touristic seasons), type of evacuation (simultaneous whole community evacuation or sequentially staged evacuation of different areas), eruption probability, exposure, timing (before, during or after the eruptive event). ABM has been used in evacuation simulation extensively (e.g. Bae et al., 2014; Hilljegerdes and Augustijn-Beckers, 2019) and it has many advantages compared to aggregate and static approaches as it allows us to incorporate individual level behaviors, event scheduling, dynamics of agent interactions, flexibility, natural description of evacuation process (Mas et al., 2019). In addition, the platform AnyLogic® allows to visually observe and assess the evacuation scenarios. A strategy to assess the economic impact of an evacuation based on the analysis of the consequences on the main economic activity (i.e., tourism) is also presented.

The next section provides some conceptual background related to effective evacuation, types of evacuation methods, and evacuation modelling, while section three describes the study area. Section four illustrates the methodology adopted in our analysis, while sections five and six present and discuss the results on the assessment of evacuation efficiency as well as the assessment of economic impact of an evacuation considering different durations and starting time of both a total and partial evacuation ~~and~~(i.e. evacuation of ~~different~~individual areas); the current unrest on Vulcano is also discussed in relation to the work presented here. Section seven provides conclusions.

2. Background on effective evacuation

Han et al. (2007) developed and described a four-tier evacuation effectiveness framework, by looking at evacuation time, individual evacuation time, exposure over time, and spatio-temporal exposure measures. Effectiveness of evacuation planning and operations for volcano emergencies can be assessed using this four-tier framework. One of the most common goals of evacuation analysis and planning is

to improve the effectiveness of evacuation by reducing evacuation time to minimize the adverse impacts associated with people leaving their place of employment, study, or their homes. Several methods have been proposed to improve the effectiveness of emergency evacuation such as enhancing the outcome of an evacuation order and ~~warning~~ dissemination of warning messages, controlling flows and movements in and out of designated areas, implementing staged evacuation, directing people to the best evacuation routes, and focusing on flexibility to plan a possible evacuation (Abdelgawad and Abdulhai, 2009; Gaudard and Romerio, 2015).

In this paper we distinguish between "evacuation time", defined as the time required for the last person to evacuate an emergency zone (Urbanik, 2000), and "evacuation duration", which represents the period during which a community has been removed from a risky area. In addition, we define "evacuation effectiveness" as the time required to evacuate a certain fraction of the population (e.g., 95%) (Han et al., 2007). Evacuation time of individuals or families depends on ~~a number~~ behavioural, logistical, perceptual, and communication factors (Tomsen et al., 2014). In order to minimize evacuation time, it is, therefore, important to reduce evacuation warning time (time it takes for the evacuation warning to reach each individual), evacuation preparedness time (time it takes for individuals to prepare for evacuation after receiving an evacuation warning), and evacuation travel time (time it takes for individuals to travel from their residence to designated evacuation ~~designated~~assembley areas). Each of these time segments varies from person~~/~~ to person and family to ~~person/~~family depending on their demographic attributes, preparedness levels, and access to information and resources (Jumadi et al., 2019, Lechner and Rouleau, 2019).

2.1 Simultaneous and Staged Evacuations

Evacuation can be implemented using simultaneous or staged methods. In the simultaneous evacuation, people in an exposed area are informed and expected to evacuate simultaneously. In the staged evacuation, the exposed area is divided into several zones, and people in each zone are evacuated according to a specific order (Sbayti and Mahmassani, 2006). Both simultaneous and staged evacuations have been used in past emergencies. Staged evacuations have been frequently used during hurricanes and for the 2002 Los Alamos wildfire in New Mexico (Malone et al., 2001; Farrell, 2005; Wolshon et al., 2006). Simultaneous evacuations are often used during sudden emergencies when rapid evacuation is necessary (e.g., earthquake, landslide, industrial accidents), whereas staged evacuation is considered more effective when sufficient lead time exists to prepare for evacuation or when resources are limited for simultaneous evacuation of the whole population. Chen and Zhan (2008) also found that simultaneous evacuations are more suited in areas of low traffic congestion, whereas staged evacuation may be the most effective in high population density areas and complex street networks. In case of staged evacuation, the number of stages can influence the evacuation effectiveness and thus optimising the number of stages is essential in reducing delays during the evacuation process (Chien and Korikanthimath, 2007). Jumadi et al. (2019) developed a staged evacuation using a spatial multi-criteria

analysis for prioritisation of evacuees and found that while the staged evacuation was more effective in reducing potential traffic congestion, the simultaneous evacuation still showed better results in reducing the population at risk.

2.2 Evacuation Modelling and Simulation

Several simulation and modelling approaches have been proposed and used for evacuation including cellular automata, game ~~theoretic~~theory, discrete events, multi-criteria decision support systems (Cole et al., 2005; Marrero et al., 2013), agent-based (Voight et al., 2000; Carver and Quincey, 2005; Jumadi et al., 2016), and experimental methods (Yang et al., 2015). Evacuation modelling has been performed for small and medium scale emergencies such as building fire, structural blast (Pluchino et al., 2015), metro stations (Wang et al., 2013), oil and gas platforms and ~~factories~~refineries (Cheng et al., 2018), and university campuses (Asgary and Yang, 2016). Larger scale emergency evacuations have also been modelled, such as volcanic eruption, flooding, and hurricane (Jumadi et al., 2016; Bernardini et al., 2017; Fahad et al., 2019).

Agent-based modelling (ABM) is emerging as a suitable and promising framework for evacuation analysis and planning in recent years (Chen and Zhan, 2008; Liang et al., 2015; Jumadi et al., 2019). ABM is appropriate for modelling complex and interactive systems (Gilbert and Bankes, 2002) such as emergency evacuation because it combines behavioural attributes with spatial and environmental data (Brown and Xie, 2006). Moreover, ABM can provide a more realistic evacuation simulation with respect to the aforementioned approaches by incorporating human agents to the geographical environment (Mas et al., 2012; Joo et al., 2013).

3. Case Study: Vulcano island, Italy

The Aeolian Islands, which earned UNESCO World Heritage status in 2000, are a volcanic arc located in the Tyrrhenian Sea (25 km north of Sicily) associated with the subduction of the African plate under the Eurasian plate. Stromboli volcano on the island of Stromboli and La Fossa volcano on the island of Vulcano are the youngest and most active volcanic edifices (Selva et al., 2020). Vulcano is the southernmost of the seven Aeolian Islands ~~located in the Tyrrhenian Sea (25 km north of Sicily). It has~~, having a surface area of ~20 km^2 and ~~contains~~containing five main urban settlements~~, i.e.~~: Vulcanello, Porto, Lentia, Piano and Gelso (**Fig. 1**). The areas of Vulcanello and Porto both have mixed land use zones with commercial, residential, and tourism activities. Piano is mostly a relatively rural residential area with one dual elementary/middle school (for children up to 14 years in age). Lentia and Gelso are small residential areas (associated with <4% of total residents on Vulcano. Vulcano has a few local critical facilities and ~~infrastructures~~infrastructure that include three helipads, one main port (Porto di Levante) and two smaller ports (Porto Ponente and Gelso), one main power plant in Porto and one secondary solar plant in Piano as well as one telecommunication station, one desalination plant and one
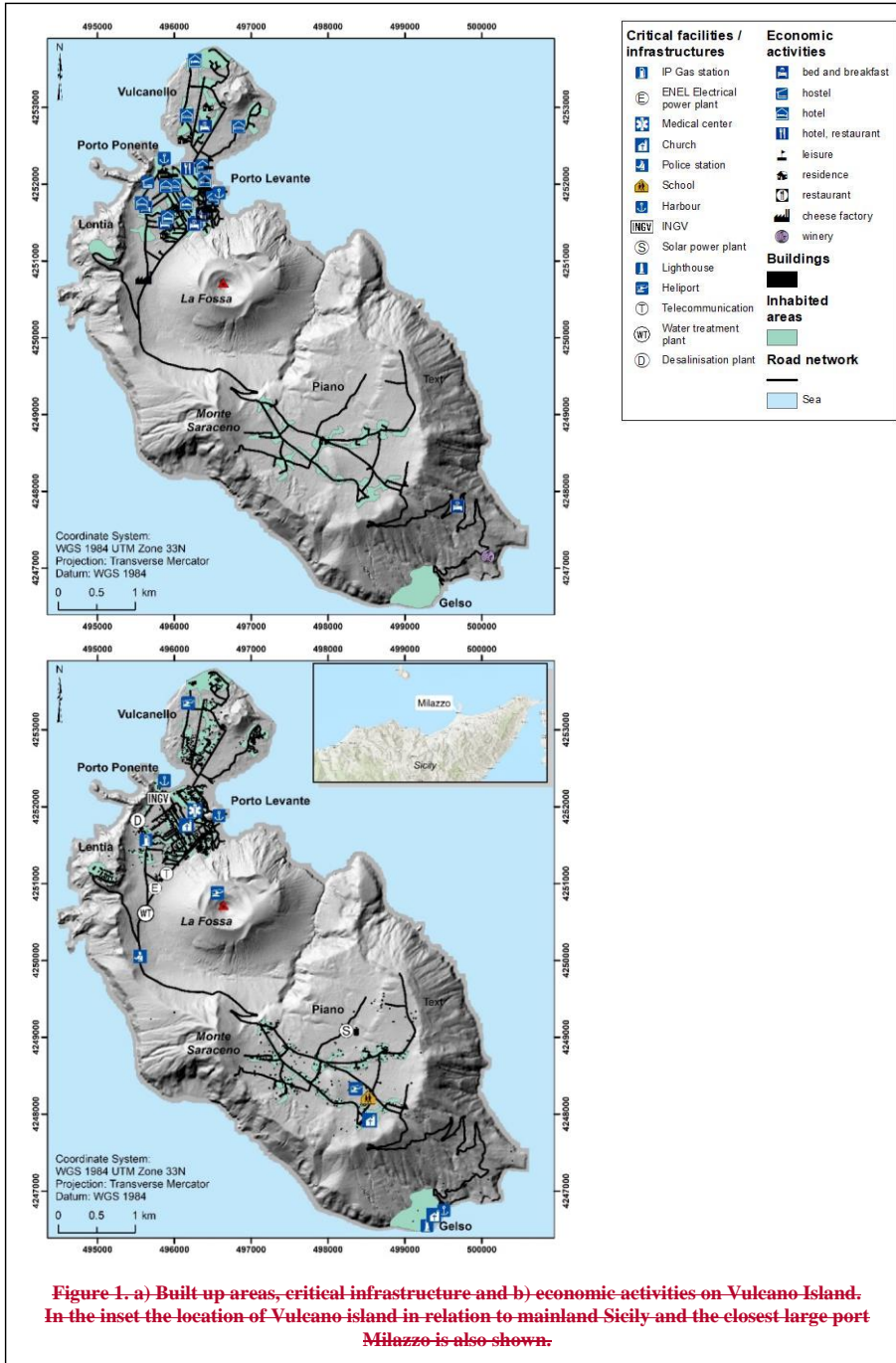
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waste-water plant in Porto. **(Fig. 1)**. The road network is limited with only one road connecting Porto
225 and Piano (Galderisi et al., 2013; Bonadonna et al., 2021).

Vulcano's predominant economic activity is tourism (Galderisi et al., 2013; Aretano et al., 2013; Bonadonna et al., 2021). The island's economy and urbanization have been growing fast since the 1980s by attracting tourists from Italy and other countries, particularly during the summer season. Vulcano has a ~~floating~~fluctuating population ~~passing~~ranging from about 800 residents in the winter to monthly peaks
230 of about 22,000-28,000 visitors in July-August (Bonadonna et al., 2021). With increasing number of visitors and seasonal workers, volcanic risk also increases ~~and, therefore, emergency~~. Emergency

management, particularly evacuation planning and preparedness, has also become an important issue for the island.

Figure 1. a) Built up areas, critical infrastructure and b) economic activities on Vulcano Island.
Inset shows the island's location in relation to mainland Sicily and the closest large port Milazzo.

Figure 1. a) Built up areas, critical infrastructure and b) economic activities on Vulcano Island. In the inset the location of Vulcano island in relation to mainland Sicily and the closest large port Milazzo is also shown.

3.1. Geological settings ~~and implications for evacuation plannning~~

In terms of geological settings, Vulcano consists of several overlapping volcanic structures including two caldera systems (~~i.e.~~Il Piano caldera to the south and La Fossa caldera in the central portion of the island), and a smaller structure (~~i.e.~~Vulcanello) in the ~~northern side of the island.~~north. A stratovolcano (i.e., La Fossa cone) ~~sits~~rests within the La Fossa caldera ~~and~~, while three smaller and coalescing pyroclastic cones sit atop the Vulcanello islet. Subaerial volcanic activity ~~in~~on the island dates to 135 ka and 120 ka (Zanella, et al., 2001), with La Fossa cone (hereafter referred to simply as La Fossa) starting at ~6 ka and being the current most active system (Dellino et al., 2011~~.~~; De Astis et al., 2013). The last eruption of La Fossa was a long-lasting Vulcanian cycle that occurred between 1888-1890 (Mercalli and Silvestri, 1891). The eruption produced emission of ballistics~~,~~ and tephra fallout, ~~and~~while intense remobilization of the tephra-fallout deposits by rainwater ~~into~~produced lahars (Di Traglia et al., 2013). The most likely hazards associated with eruptive activity of La Fossa are tephra fallout (including ballistic projectiles) and pyroclastic density currents as well as gas emissions, volcanic debris flows, lahars, ground deformation, and seismicity that can also occur during the quiescent and unrest states (Selva et al., 2020). However, it is also important to consider that the activity of La Fossa has been characterized by a large variety of eruption styles, including effusive activity and explosive events. Among this variety, hydrothermal events of various intensity have occurred and associated with impactful hazards such as blast, diluted PDCs and ballistic fallout, with the most violent being the Breccia di Commenda eruption dated around ~~1230~~1300 (Rosi et al., 2018; Pistolesi et al., 2021). It is thus important to distinguish between magmatic events, for which the main driver is the magma rising to the surface, and hydrothermal (or phreatic) events, for which the main driver is the interaction amongst water, rocks, and magmatic heat and gas (e.g~~.~~., Barberi et al., 1992; Rouwet et al., 2014; Stix and de Moor, 2018). By their nature, hydrothermal events may be more difficult to predict than magmatic unrests and they can also happen outside the main active vent (as it has often been the case at La Fossa). In fact, the La Fossa system is a permanent and powerful emitter of fluids whose flow is maintained by an elevated gas over-pressure in the subsoil (Selva et al., 2020). Even modest ~~imbalances~~disequilibrium in the supply of fluids can trigger explosive eruptions as the numerous cases that have occurred on Vulcano after the Breccia di Commenda in the last eight centuries demonstrate (e.g~~.~~., 1444 AD, 1550 AD, 1727 AD, 1873-76 AD; Selva et al., 2020). This is also the case of other volcanoes that have been associated with recent and sudden explosions such as White Island and Tongariro in New Zealand (Breard et al., 2015; You Lim and Flaherty, 2020), Ontake in Japan (Oikawa et al., 2016) and Turrialba and Poas in Costa Rica (Alvarado et al., 2016; de Moor et al., 2016). ~~While at most~~ Most of these volcanoes ~~mentioned above that~~ are located in remote areas ~~these hydrothermal~~sohydrothermal events represent a threat mostly for tourists~~,~~ in close proximity to them, but in Vulcano they represent a serious threat also for ~~inhabitants~~residents that live very close to the volcano (e.g~~.~~., Porto area on the north of La Fossa). The main infrastructures (including two ports - Porto di Levante and Porto di Ponente, the telecommunication station, and the main power plant) and the

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majority of economic and touristic activities are concentrated in the Porto area also located just north of La Fossa cone (**Fig. 1**). ~~This is why~~Therefore, in the case of Vulcano, the potential for evacuation becomes an important issue even in case of weak unrest. Both a hydrothermal explosion and a magmatic eruption would be especially challenging events during which to manage an evacuation if they happened during the high season (July-August) and with little or no warning, as it has been the case for the recent small but deadly eruptions at touristic places mentioned above.

3.2 Civil Protection System in Italy

In order to reduce the potential volcanic impact, scientists, including those of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), of selected research institutions ("Centri di Competenza") and of the Consiglio Nazionale delle Ricerche of Italy - Institute for electromagnetic sensing of the environment (CNR-IREA), continuously monitor all active volcanoes in Italy, including La Fossa, periodically transferring information on the state of volcanic activity to the national and regional decision makers each with defined authorities, roles and responsibilities; all these institutions are part of the overall Civil Protection System in Italy (Legislative decree "Codice della protezione civile", 2018). In Italy, in fact, civil protection activities are not assigned to a single body, but represent complementary tasks attributed to an integrated system composed of both public and private and both national and territorial (regional and local) structures. The Italian Civil Protection Department (at the national level) is a structure of the Presidency of the Council of Ministers and coordinates the entire Civil Protection System.

Another important aspect to consider is that volcanic risk management in Italy is based on an alert level system and the Italian scientific community have defined four Volcanic Alert Levels based on monitoring parameters that describe the state of activity of each Italian volcano. These levels correspond to four colors (green, yellow, orange and red), which are indicative of the level of activity and to its possible evolution, including the shift from local to national impact scenarios. In fact, volcanic activity can also generate local impact events, which are managed at the local level by the appropriate institutions (i.e. regions and municipalities). Recently, the Italian Civil Protection Department financed detailed studies to improve the current understanding of the volcanic system and the whole range of potential volcanic hazards on Vulcano Island (Selva et al., 2020). Based on these results, an updated version of the Alert Levels for Vulcano were issued at the end of 2021. These Alert Levels have been included in the National Civil Protection Plan for volcanic risk on the island. The plan also describes the "national level operational phases", which include the mitigation actions that all the stakeholders involved in the emergency management must take and foresees the evacuation of the population before the eruption onset in case of increasing volcanic unrest.

3.3 Potential consequences of a volcanic crisis on Vulcano

Although it would appear to be a quick and small operation, evacuation of the island under different weather and marine conditions, occurrence of different hazards (~~e.g.~~gas, tephra fall, PDCs, lava flows,

lahars, landslides, tsunami) and various seasons (summer versus winter) could result in different

310 decisions and actions. Moreover, one must also account for unforeseen factors that might limit the availability and efficiency of evacuation (e.g., damaged ports). In addition, forecasting volcanic eruptions and managing volcanic crises represent an important challenge for both scientists working in observatories (e.g. geochemists, geophysicist, geologists, volcanologists) and civil authorities such as those associated with emergency management (i.e. Civil Protection System in Italy). Many impediments

315 may be encountered in interpreting key aspects such as: i) whether or not unrest will lead to an eruption, ii) the nature of explosive activity (magmatic or hydrothermal), iii) the eruptive style (i.e., effusive, explosive or both), iv) the potential activation of lateral vents, v) the eruption magnitude (i.e. erupted volume) and intensity (i.e. the rate of discharge of magma, plume height), vi) the type, extension and timing of hazards with the potential to impact human life and the infrastructure supporting evacuation

320 whether occurring either in the unrest phase or eruptive phase or both. The interpretation of scientific data complicates the decision-making process for the officials (Fearnley, 2013). , damaged harbours). Scientists including those of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and of the Consiglio Nazionale delle Ricercheof Italy – Institute for electromagnetic sensing of the environment (CNR-IREA) continuously monitor all active volcanoes in Italy, including La Fossa, periodically

325 transferring information on the state of volcanic activity to the national and regional decision makers each with defined authorities, roles and responsibilities that are part of the overall Civil Protection system in Italy (Legislative decree "Codice della protezione civile", 2018). Evacuees may include local residents, national and international tourists, and seasonal workers. While a general municipal plan for emergency management on Vulcano exists (http://www.comunelipari.gov.it/zf/index.php/servizi-

330 aggiuntivi/index/index/idservizio/20015), and an evacuation drill was carried out with the residential population in 1991 after a period of seismic unrest at La Fossa, a detailed and updated evacuation plan for the Vulcano island does not currently exist. Recently, the Italian Civil Protection Department has undertaken a dedicated effort to finance detailed studies of the current understanding of the volcanic system and of the whole range of potential volcanic hazards (Selva et al., 2020). Based on these results

335 the alert level system is being reviewed in collaboration with the scientific communityHigher levels of scientific uncertainty may thus translate in increased difficulty for emergency managers to understand the value of evacuation (measured in terms of human lives saved) and the costs associated with any evacuation associated with unrest that does not result in eruption.

When a volcano begins to show increasing signs of unrest above background level, authorities must deal

340 with uncertainties and decide how to manage a potential crisis (e.g., have people shelter in place or evacuate some or all of the population), as scientists cannot guarantee if the unrest will result in an eruption or not. Although successful forecasts have been made (e.g., Mt St Helen's 1980, USA; Mt Redoubt 1989-1990, USA; Pinatubo 1991, Philippines), alarms raised that are not followed by hazards impacting exposed areas sometimes cause both scientists and other officials to lose credibility among

345 the public (e.g., Sparks, 2003; Tilling, 2008). In addition, a volcanic crisis can easily result in an

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economic crisis, with or without an evacuation and an eruption occurring. Interesting examples are those of the 1983-1985 volcanic crisis at Rabaul Caldera (Papua New Guinea) and of the 1999 volcanic crisis of Tungurahua volcano (Ecuador). In the first case, a dramatic short-term increase in seismicity and ground deformation led to an intensification of disaster-preparedness activities and voluntary evacuations by villagers, which resulted in substantial losses of revenue due to business interruptions and a large cost of emergency preparations; at the end, many people thought that two years of preparation was a waste of money even though public awareness of potential volcanic hazards increased and the community became more resilient (Hastings, 2013; Tilling, 2008). In the second case, an economic crisis at both local and national level resulted from an evacuation that followed a successful forecast as most of the community's economic activity depended on tourism (Lane et al., 2003). This is also valid in the case of Vulcano Island. Even without an evacuation order, the increasing level of unrest may cause the local people to leave the island if they believe that tourism on the island may be affected negatively by the increasing volcanic activity. This is especially true since most business owners are not from Vulcano and they may decide to relocate their activities. In both cases, the economy of the island would be negatively impacted. Additionally, there could be significant negative economic impacts on Vulcano associated with changes in the volcano alert level even when an eruption or evacuation does not occur, as Peers et al. (2021) described for the protracted unrest at Long Valley Caldera, California, in the USA. Volcanic unrest and eruptions can also have positive impact on economy. As an example, volcano geotourism has become increasingly popular around the world (e.g. Dóniz-Páez et al. 2020; Quesada-Román and Pérez-Umaña 2020). It is estimated that between 150 and 200 million people visit volcanic and geothermal environments on an annual basis (Brace, 2000; Heggie, 2009; Bird et al. 2010; Erfurt-Cooper and Cooper, 2010; Erfurt-Cooper, 2011). Vulcano Island appeals to a wide range of tourists: some visit to relax and/or for health reasons, whereas others are attracted to volcanic landform and geothermal features. Thus, an increase in unrest may attract more adventure-driven tourists, unless such visits are curtailed by civil authorities as a result of increased likelihood of eruption and resulting limitation of the number of people on the island. If the increasing activity on the island results in an evacuation and finally in an eruption, still many tourists interested in natural areas and adventure may want to visit the island once the activity is back to pre-eruption and the risk is decreased.

4. Methods

4.1. Agent-Based Modelling of pedestrian evacuation

The Vulcano evacuation simulation toolEvacuation Simulation Tool has been developed using the Anylogic platform (version 8.7.5), which provides ABM capabilities as well as GIS spatial data incorporation. Our simulation tool includes four main agents, each of which is described below (i.e. Hazard, Evacuees, Ferries and Ports, Agents' Environment). In order to correctly characterize such agents and tailor the analysis to the specifics of the island without which the tools would be useless, risk factors including hazard, vulnerability and exposure of both the community and critical assets must be

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known as well as their dynamics over time ~~during the year and the different seasons.~~. Such key elements have been extensively addressed and analyzed in a paper presenting a novel risk assessment model for volcanic risk, named ADVISE, based on long term research efforts of the authors and applied to ~~the~~ Vulcano Island (Bonadonna et al., 2021). All the needed aspects and elements required to assess the various indicators are provided there and rely on an extended work of surveys and data collection carried out in the last ten years. The following ABM uses the outcomes of such data collection and risk assessment, especially as far as hazard and exposure are considered. Some aspects of systemic vulnerability are also considered related to the accessibility of the three ports of the ~~Island~~island and their intrinsic characteristics.

4.1.1 Hazard (volcano) agent

We define La Fossa volcano as a physical agent with specific behaviour and states. defined based on scientific evaluation. It is important here to differentiate between the state of the volcano (Quiescence, Unrest, and Impending/Ongoing eruption) with Alert Levels (Green, Yellow, 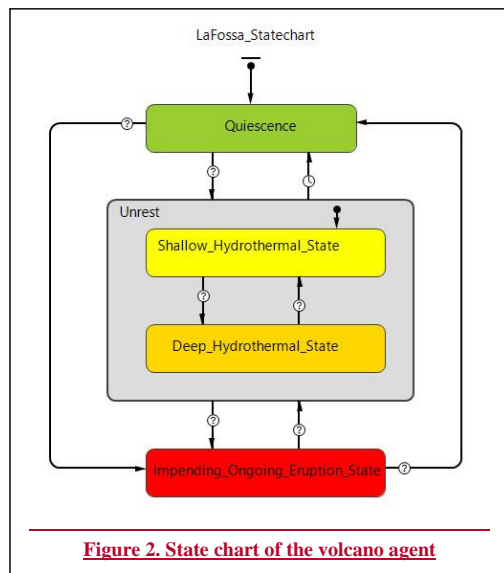Orange and Red) typically identified by the Civil Protection Department. In this ABM, La Fossa volcano has three main states including ~~background level~~Quiescence (i.e. normal conditions), ~~unrest (devided~~Unrest (divided into ~~Attention, Pre Alarm, Alarm) and eruption~~shallow hydrothermal crisis and deep hydrothermal crisis) and Impending or Ongoing eruptive activity (**Fig. 2**). It is important to consider that, for ~~simplicity,~~the sake of illustration, these states ~~in this ABM are general states and do not correspond to the alert~~have been simplified with respect to the Alert Level system specific to Vulcano, ~~which is still under evaluation. However~~

Figure 2. State chart of the volcano agent

(https://rischi.protezionecivile.gov.it/it/vulcanico/vulcani-italia/vulcano). In any case, modifications can be made to reflect the specificities of individual volcanoes. ~~Normal conditions vary~~Both the Quiescence and Unrest state are different for ~~each volcano; in~~different volcanoes. In Vulcano, ~~they consist~~the Quiescence state mostly consists of fumarolic emissions (mostly concentrated in two main fumarolic fields located in the northern rim of the active crater of La Fossa cone and at the beach of Baia di Levante, in Porto Levante area), ground deformation, earthquakes and accompanying landslides (Barberi et al., 1991; Selva et al., 2020~~). While~~), while the Unrest state is mostly related to a shallow or

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deep activity of the hydrothermal system associated with various levels of increase in the flux and temperature of gas emissions combined with seismicity and deformation of the volcanic edifice. As already mentioned, phreatic eruptions can occur in all these volcano ~~agent can be very complex, here we only include the volcano behaviours and~~ states ~~that impact the evacuation process. As such~~with little or no warning. However, in our model, we assume that the simulation of evacuation starts before an eruption when the volcano is in the ~~Alarm~~Impending eruptive state (**Fig. 2**). ~~In the Alarm state, eruption is assumed to be imminent or highly likely such that a mandatory evacuation order is issued.~~
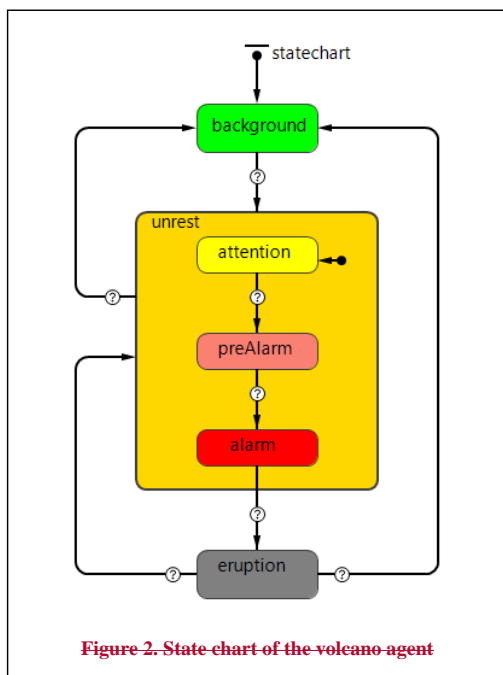
Figure 2. State chart of the volcano agent

~~Shift from Alarm state to the Eruption state is handled through a condition transition that is linked to a user defined table function.~~2). Forecasting of a volcanic eruption can be based on various functions ~~discussed in literature~~, e.g. exponential hazard function (Ho, 1992; Cornelius and Voight, 1994; Chastin and Main, 2003; Connor et al., 2003; Cruz-Reyna and Reyes-Dávila, 2001). The spatial exposure of evacuees can also be determined based on the probability of being impacted by an eruption using Aucker et al. (2013) and Brown et al. (2017) models as well as hazard analyses of Vulcano (Dellino et al., 2011; Biass et al., 2016a, 2016b; Bonadonna et al. 2021; Gattuso et al., 2021). The probability of being impacted by various volcanic hazards depends on eruption dynamics (i.e., occurrence of ballistics, tephra fallout, lava flows, blast surge-like PDCs, lahars) as well as topography and atmospheric conditions (e.g., wind speed and direction). Hazard maps for Vulcano exist that describe the potential extent and intensity of tephra fallout and ballistic projectiles (Biass et al. 2016a,b), pyroclastic density currents (Delling et al., 2011) and lahars (Gattuso et al. 2021). However, given that before the actual eruption (~~hydrothermal~~phreatic or magmatic) takes place, the extent and intensity of the associated hazards are not known, we consider here the evacuation of certain areas to be based on the worst-case scenario, e.g. occurrence of PDCs and ballistic ejection in the case of Vulcano, which could impact the whole La Fossa Caldera (including Porto area) and part of Piano Caldera (e.g., Dellino et al., 2011; Biass et al., 2016b).

4.1.2. Evacuee Agent

455 We combined and expanded the Sorensen and Mileti (2014) and Stepanov and Smith (2009) multi-step evacuation process models to include four main time segments: 1) warning issuance, the step from when unrest or evidences of hazard appear to when decision makers decide to issue the warning; 2) warning diffusion, the process from when the warning is issued to when the warning reached the intended audiences; 3) ~~evacuation decision and preparation; and 4) evacuation movement.~~preparation for

460 evacuation, the process from when the warning reached the intended audience to when they are ready to evacuate (this includes the time required to organize departure and secure the belongings that are left behind, e.g. house, car(s), other vehicles, boats); and 4) evacuation movement. A statechart is used to
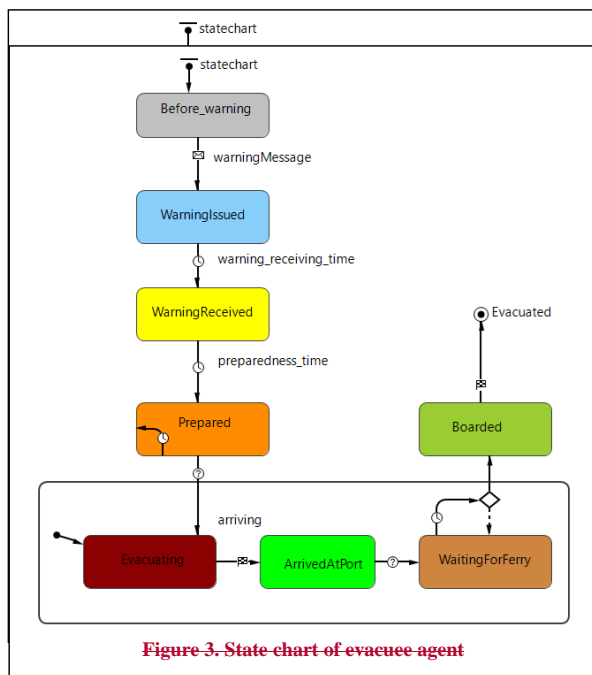
Figure 3. State chart of evacuee agent

model the evacuee agent's evacuation behaviour (**Fig. 3**). The agent is created, and its initial state is set to "before warning" (or normal). As soon a warning is issued, the agent's states change from "before warning" to "warning issued", corresponding to an evacuation order. Transition from this state to the "warning received" is controlled by a time out triggered transition. We use a normal truncated distribution for this transition with minimum and maximum time values that can be set by evacuation planners before running the simulation. Use of this distribution allows us to limit

the lower bound to 0 and the upper bound to a finite value. Transition from the warning received state to prepared state is also handled by a truncated normal distribution that can be set by the evacuation planner. However, this transition is triggered only if the evacuation is either a simultaneous evacuation or the evacuee is located in the assigned evacuation stage.

485 The order of evacuation during a staged evacuation is based on the proximity to the hazard, with the most exposed people being evacuated first. In Vulcano, the ~~North~~north part of the ~~Island~~island will be evacuated from the Levante and Ponente ports and the ~~South~~south of the island from the port of Gelso. In our simulations, people in Porto and Piano will be simultaneously evacuated first, and people in Vulcanello will be evacuated last. However, to provide the emergency planner with more flexibility, the

490 simulation allows the users to set the evacuation order as needed. Evacuation time depends on the evacuees' pedestrian speed and their distance to the closest active port. We consider the walking speed

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as a uniform distribution, but the model allows the lower and upper bounds of this distribution to be set depending on the environmental situations and population scenarios being ~~analyzed~~analysed. We assume here only pedestrian evacuation, but the simulation can be adapted to also include evacuation by vehicles, or a combination of the two. We recognize that while walking may be a more feasible option for those in the north part of the Island~~,~~ (Vulcanello e Porto), it may be more difficult for the people in the south part of the island~~.~~ (Piano). Upon arriving at the closest active port, evacuees wait for ferries. ~~Once the ferries arrive~~Given that our simulations are based on the assumption that the evacuation takes place before the eruption, evacuees ~~board and they~~ are considered to be evacuated once the ferries arrive and are boarded. However, in case the evacuation was carried out during the eruption, people should be considered evacuated once the ferries actually leave the ports, as both ports and ferries could be impacted by the eruption.

4.1.3 Ferries and Ports Agents

Figure 4. State charts of a) ferries and b) ports agents
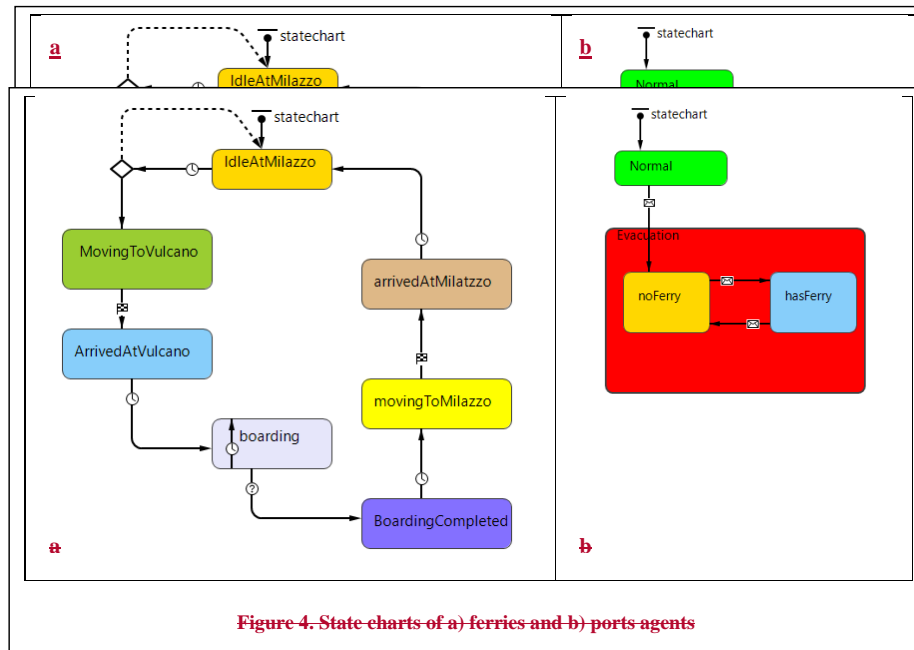
Ferries transport evacuees from ports on Vulcano southward some 44 km to the large port of Milazzo on the north shore of Sicily (**Fig. ~~1~~1a** inset). As an evacuation order is issued, ~~available~~ ferries are mobilized in the Milazzo port. ~~It takes between 40 minutes to 1 hour for ferries (hydrofoils) to reach the Porto Levante in Vulcano from Milazzo.~~ In our simulations, ferries ~~will~~ have ~~a~~the capacity ~~ranging from~~of 200 ~~(hydrofoils) to~~, 400, 600 and 800 ~~(ferries)~~ passengers ~~(including intermediate capacities of 400 and 600),~~and an average speed of 50 km/hour, but these variables can be changed. ~~Since the two smaller ports in Vulcano (Porto Ponente and Porto Gelso) are not suitable for large ferries, only boats~~

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with small capacities are dispatched to these ports. BoatIn fact, ferry speed depends on the weather and marine conditions that can be set by the users before running the simulation. However, for this study we use an average speed of 50 km/hour that is the regular speed of hydrofoils boats operating between Vulcano and Milazzo. As shipsferries arrive in theirto the port, evacuees start boarding until full capacity is reached, at which point ships willthey travel back to Milazzo. If there are more requests, ferries and boats continue going back to the assigned Vulcano ports, otherwise they stay in Milazzo.

Port agents have two main states in our ABM including Normal and Evacuation states (**Fig. 4**). As soon as an evacuation order is issued, the state of the ports changes from Normal to Evacuation through a message transition. Inside the evacuation state, two substates demonstrate whether a port has ferries to board evacuees or not. The transition between these two substates is controlled by the interactions between the ferries' agents and ports' agents.

4.1.4 Agents' Environment

Two main GIS networks were created for this study. The first connects the three ports of in Vulcano (Porto Ponente, Porto Levante and Porto Gelso) to the port in Milazzo (**Fig. 1a**). The second connects buildings in Vulcano (e.g., residential, commercial, hotels, facilities, etc.)) with the road network created based on the existing road network on the OpenStreetMap (**Fig. 1a,b1**).

4.1.5 Model setup

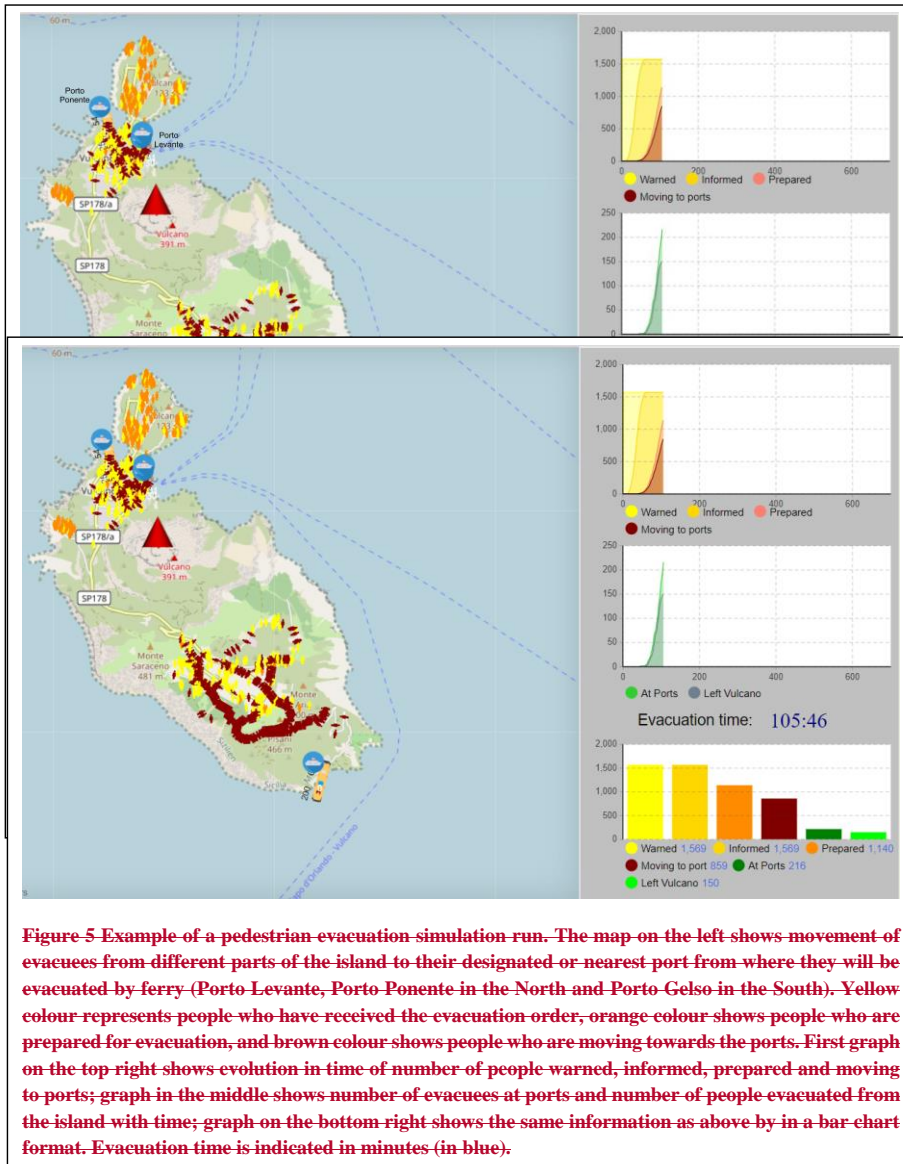| Parameter	Description
Warning received time (minutes)	Uniform distribution, between 15–90
Preparedness time (minutes)	Uniform distribution, between 30– 120
Walking speed (m/s)	Uniform distribution, between 0.8–1.6
Population (low season)	Total: 1,000
	Piano: 300
	Vulcanello: 100
	Porto: 600
Population (high season)	Total: 4,600
	Piano: 400
	Vulcanello: 400
	Porto: 3,800
Number of available ferries	10
Capacity range of ferries (number of passangers)	200, 400, 600, 800
Average speed of ferries (km/h)	50
Evacuation order for staged evacuation	First stage: Porto (via Gelso) and Piano (via Levante and Ponente)
	Second stage: Vulcanello (via Levante and Ponente)
Table 2: Input conditions to the model and selected values used for the scenarios considered for Vulcano. All these parameters can be adapted to the user's need.	

We illustrate our evacuation simulation tool by setting up two pre-eruption evacuation scenarios taking place during the low and the high touristic seasons. Summary of the scenario's initial conditions are summarised in **Table 2**. **Figure 5** and **Appendix A** show the parameters and scenarios setting and the

Parameter	Description
Warning received time (min)	Uniform distribution, between 15–90
Preparedness time (min)	Uniform distribution, between 30–120
Walking speed (m/s)	Uniform distribution, between 0.8–1.6
Population (low season)	Total: 1,000 Piano: 300 Vulcanello: 100 Porto: 600
Population (high season)	Total: 4,600 Piano: 400 Vulcanello: 400 Porto: 3,800
Number of available ferries	10
Capacity range of boats (number of people)	Hydrofoil: 200 Ferry: 800
Average speed of ferries (km/h)	50
Evacuation order for staged evacuation	First stage: Porto (via Gelso) and Piano (via Levante and Ponente) Second stage: Vulcanello (via Levante and Ponente)

Table 2: Input conditions to the model and selected values used for the scenarios considered for Vulcano. All these parameters can be adapted to the user's need.

main interface of the Vulcano Evacuation Simulation Tool. The low season scenario involves 1,000 people consisting of 300 local residents living in Piano, 100 residents living in Vulcanello and 600 people classified collectively fromincluding residents, seasonal workers and tourists in Porto. The high season evacuation involves a total population of 4,600 consisting of 400 people each in Piano and in Vulcanello and 3,800 people in Porto, where residents, tourists and seasonal workers are mixed across the different areas (for. For the sake of simplicity here we only consider Porto, Piano and Vulcanello areas as Lentia and Gelso are associated with <4% of the residents). Both scenarios assume only pedestrian evacuation, where each evacuee is assigned a walking speed uniformly sampled between 0.8 m/s to 1.6 m/s (Wood et al., 2018). The evacuation warning time follows a uniform distribution between 15 and 90 minutes and the evacuation preparedness time also has a uniform distribution ranging between 30 and 120 minutes (**Table 2**). In addition, our simulations do not account for variable weather and marine conditions. Note that these parameters were chosen based on the author'sour knowledge of the area and are used only with the purpose of illustrating the functionality of the tool. All parameters can and should be identified by emergency managers based on the availability of information and on the

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range of conditions to be tested (e.g~.,. people with reduced mobility or with health issues, evacuation using a variety of vehicles).

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Figure 5 Example of a pedestrian evacuation simulation run. The map on the left shows movement of evacuees from different parts of the island to their designated or nearest port from where they will be evacuated by ferry (Porto Levante, Porto Ponente in the North and Porto Gelso in the South). Yellow colour represents people who have received the evacuation order, orange colour shows people who are prepared for evacuation, and brown colour shows people who are moving towards the ports. First graph on the top right shows evolution in time of number of people warned, informed, prepared and moving to ports; graph in the middle shows number of evacuees at ports and number of people evacuated from the island with time; graph on the bottom right shows the same information as above by in a bar chart format. Evacuation time is indicated in minutes (in blue).

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4.2 Assessment of the economic impact of an evacuation

When the hazard level is high and human life is at stake, economic losses usually play little to no role in the decision of whether to evacuate. In less extreme situations, however, authorities weigh different factors, and different evacuation plans can be considered. In fact, the management of the crisis will take different courses depending on the evolution of the unrest and the time-dependent evolution of the hazard. Accurate data necessary for a reliable cost-benefit analysis are rarely available, especially in the context of small islands where they are aggregated at the level of the Municipality. Furthermore, in case of relatively simple economic systems such as that of a small island, complex and sophisticated models can be replaced by a set of reasonable hypotheses. Consequently, we present an approach to estimate the loss of revenue caused by a total or partial evacuation of the population on the island at any one time (i.e. residents, seasonal workers and tourists) due to an imminent eruption. Such an analysis is especially important in case of scenarios of long-lasting Vulcanian cycles, such as that of the 1888-90 eruption of La Fossa volcano, that would disrupt the island's economy for a long time (many months to years).

Data collection required to estimate the impact of an evacuation on the island's main source of revenue was carried out between 2014 and 2016. This investigation focused on tourism related business activities. We interviewedspoke with owners and workers of shops, restaurants, hotels, and a tourist office in May 2014 to constrain working seasons, business hours and consumer prices. We also spoke with the tourist office in Lipari to determine the number of tourists visiting Vulcano. This was supported with online research (2014-2016) to assess hotel prices that could not be obtained through discussions with personnel onsite. Several booking websites were used in case the hotel did not have its own website. While there are two main beaches between Porto and Vulcanello that serve as the main attraction for visitors overall, one of the most popular touristic activities on Vulcano is the mud pool. in the Porto Levante area. The mudpool sits on a fault lineament between La Fossa and Vulcanello and was initially developed around an exploration drilling site for geothermal exploitation drilled in the 1950s (Faraone et al., 1986; Gioncada et al., 1995). Many people visit the island only for this reason. Tourists mostly come to the island during summer and in addition to visiting the mud pool they also like to taste the local cuisine, to and take boat tours around Vulcano and/or around other Aeolian Islands. Hiking to and around the summit of La Fossa and daily visits to other islands are also popular activities. A variety of lodging and accommodation solutions are available on the island (**Fig. 1b**).

At the time of our survey in 2014 and web search in 2016, there were 17 hotels on Vulcano with only four of them open the whole year (**Fig. 11b**). Those open during the middle season are not fully occupied. On the contrary, fromFrom June until September, they all operate almost at full capacity. In addition to the hotels, there were 21 B&Bs, hostels and residences with two camping areas, as well as 40 apartments. All of them are open in the high season; few are open in the middle season. Most of the restaurants are closed during the low and middle seasons. From June to September, all 24 restaurants were open until after midnight and were always full of tourists. Both day trippers from Sicily and other Aeolian Islands and visitors over-nighting on the island dine in these restaurants. Vulcano has dozens of stores located

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in the Porto area, mainly consisting of clothing and souvenir shops, but very few of them are open during the whole year. The rest are open mostly around Easter until the end of October. One main supermarket and two smaller grocery stores are located in the Porto di Levante area, which is the area within the broader Porto area defined by the presence of the main port on the island (Levante) and relatively dense development. Like most of the Aeolian islands, Vulcano has many notable activities for outdoor enthusiasts. Most all leisure activities (e.g~~.~~., mud pool, motor car and motor bike rental, bicycle rental, SCUBA diving) on the island are in the Porto and Vulcanello areas, although a few hiking trails exist in the Piano area and more remote area of Gelso in the far south of the island. Most activities are closed during low season, but a very few are in service during the middle season.

Three seasons have been identified based on the number of tourists, which include: Low Season (November ~~April~~ to March) with no touristic activity on the island (most of the hotels, hostels, B&~~B's~~Bs and residences usually undergo maintenance activities); Middle Season (April-May-June and September-October) with a gradual increase/decrease in number of tourists (some of the restaurants, hotels, hostels and B&~~B's~~Bs open; repair of residences continues during ~~this season~~April to June); High Season (July-August) with monthly peaks that approach 22,000-28,000 visitors (~~e.g.~~ 18-23 times the number of residents; Bonadonna et al., 2021). Being the closest island to Sicily, Vulcano is an easy getaway for mainland day trippers~~; lots~~, many of them coming to the island on their private boats and dining at the restaurants. In fact, buoys are available in Levante Bay and mooring is possible at the "Marina di Vulcanello" jetty to the north of the bay or the "Baia di Levante" jetty to the bay's south inside the commercial port. All types of leisure activities and shops are functional during the High Season.

Cheese and wine are also produced on Vulcano. The cheese factory La Vecchia Fattoria is situated in the west side of Porto and just off the road to Lentia. In 2016, the owner indicated that the farm included 280 goats, 40 cows and 30 sheep and the main production takes place between March and October, i.e. middle and high seasons. From November until February they have less goat milk because the goats are pregnant and/or feeding their lambs. While they have only a few clients in mainland Italy, exports are limited mostly to the Aeolian Islands, especially with supermarkets in Lipari where the main income is derived. The main wine factory (Punta dell'Ufala) is located in Gelso and the vineyards are dispersed on 5 hectares of slightly steep hills between Piano and Gelso. According to personal communication with the owner (Ms Paola Lantieri) in 2016, the most delicate season for the grapes is between March and July, because this is when the vineyard flourishes and becomes more susceptible to pests. They sell the wine mainly in Vulcano to hotels, restaurants and the grocery stores/supermarket and export some product to the mainland Italy and the USA and Japan rather than the other Aeolian Islands.

4.3 Methodology to calculate the revenues from touristic business activities in Vulcano

Our analysis focused on the turnover created by tourism-related businesses, which provides the main income to the island's economy. The turnover represents the gross revenue that a business generates

without considering associated expenses (e.g., food, water, energy and maintenance). The economic impact associated with an evacuation of the island is represented by the loss of this revenue. This revenue must not be confused with the added value provided by the national accounts, which includes the profits, wages, interest and amortizations, but not the intermediate goods and services. We do not consider the revenues from the grocery stores, supermarket and shops due to lack of sufficient reliable data nor the revenues from the cheese and wine factories because they are not tourism-related businesses. The income from maritime transport is also not included, because it does not have a major impact on the local economy.

As mentioned in **Table 1**, different categories of costs are concerned when dealing with impacts from natural events such as those involving volcanic unrest and eruption that might necessitate an evacuation of people from the island. Our focus on Vulcano was identifying tangible business interruption cost related to interruption of touristic activities. The revenues, expressed by the turnover, for all the touristic activities on the island, which will become the loss in case of an evacuation, are calculated for different seasons as part of the cost assessment. The main touristic business on the island can be divided as B&B'sBs, hostels and residences, restaurants and bars, hotels, leisure activities and shops. Each of these are described below.

4.3.1 B&Bs, hostels and residences

Data were collected from the internet and field interviews for seven7 B&B, oneBs, 1 hostel and six6 residences (out of 21), but: we were unable to obtain data for seven otherthe remaining 7 structures due to lack of online information). The revenue for each season is calculated by multiplying the capacity, the price, the total days and the occupancy rate. In the equations below, H and M indicate high and medium season, respectively.

$$RH = C * PH * TH * OH \qquad \text{(Eq. 1)}$$
$$RM = C * PM * TM * OM \qquad \text{(Eq. 2)}$$

RH and RM represent the total revenues for high and middle season, respectively. C representrepresents the total capacity, i.e. maximum number of people that can be accommodated, at a given place. PH and PM are prices per night per person; TH and TM are number of total days estimated in calculations and OH and OM are occupancy rates, i.e. the proportion of available accommodation occupied. As there are no official statistics available, simple assumptions are made for occupancy rate that are based on observations done over more than 10 years of research on the island, which are expected to be reasonable within a margin of 5-10%. During high season, a rate of 100% is estimated and for middle season, the value of 50% is used.

4.3.2 Restaurants and bars

Dine-in data (i.e. meal prices and total days open) was collected from discussions with owners/workers at 11 of the 24 restaurants and bars, but "take-away" (dine-out) revenues are not included. For this

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category the meal prices do not change with different seasons. The revenue is calculated by multiplying the capacity, average meal price, the table turn, the total days and the occupancy rate. In the equations below, H, M and L indicate high, middle and low season, respectively.

$$RPD = C * \text{Approx. meal price} * TT \qquad (Eq.\ 3)$$
$$RH = RPD * TH * OH \qquad (Eq.\ 4)$$
$$RM = RPD * TM * OM \qquad (Eq.\ 5)$$
$$RL = RPD * TL * OL \qquad (Eq.\ 6)$$

RH, RM and RL are the total revenues for high, middle and low season, respectively. The capacity C, i.e. the total number of people the restaurant can host, is multiplied with the approximate meal price and table turn TT, i.e. number of times a table is occupied with different groups, to calculate the revenue per day RPD.

It is important to notice that, ~~when it comes to the~~during high season H, the number of times a table can be occupied during working hours varies for each restaurant. For example, at Faraglione, which is small but popular restaurant and bar adjacent ~~and open~~ to the port at Levante, one table may turn as much as 20 times during a day because it is open from very early morning until very late at night. However, for middle and low season, the time a table turns is fixed at '1', considering a restaurant never works on full capacity during these seasons. TH, TM and TL represent the number of total days and OH, OM and OL represent the occupancy rate for high, middle and low season which is 100%, 50% and 15% respectively.

4.3.3 Hotels

We were able to collect the required data (capacity, prices, opening season) for 12 out of 17 hotels. As for the other missing facilities, there was no official website or they were not open for us to speak with them when data were collected. In the equations below, H and L indicate high and low season, respectively. ~~M1 and M2 represent the two subgroups of~~M represents middle season.

$$RH = C * PH * TH * OH \qquad (Eq.\ 7)$$
$$\sout{RM1 = C * PL * TM1 * OM1} \qquad \sout{(Eq.\ 8)}$$
$$\sout{RM2}RM = C * PM * \sout{TM2 * OM2}\ TM * OM \qquad (Eq.\ \sout{9}8)$$
$$RL = C * PL * TL * OL \qquad (Eq.\ \sout{10}9)$$

RH, ~~RM1, RM2~~RM and RL are the revenues for high season, middle season ~~(M1 and M2)~~ and low season, respectively. ~~In contrast to~~PH, PM and PL indicate the ~~seasonal classification~~price of ~~restaurants, hostels~~a room for high, middle and ~~B&B's,~~low season. Even though the middle season ~~for hotels is divided~~could be subdivided into two ~~subgroups due to high differences in prices. The first subgroup includes May and October, while~~groups as the ~~second one includes~~months of June and September~~. These months are considered together because the price per night per person is more or less~~ are busier than those of May and October, the same value was assumed, considering the ~~same. When~~

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calculating the revenue for the first subgroup, the price by night is the one that is used for the low season even though we are on middle season. TM1limited data. TH, TM and TM2 areTL represent the number of total days for May-October (62) and June-September (60). OM1OH, OM and OM2 areOL represent the occupancy rate for high, middle and low season which is estimated as100%, 50% and 60% in calculations for May and October and June and September,15% respectively.

4.3.4 Leisure activities

While touristic attractions contribute an important amount of revenue to the economy of the island, they close for the low season like B&B's-sBs and hostels do, because there are insufficient numbers of tourists to keep the businesses open. The type and price of leisure activities are all determined based on discussions with the owners. The revenue per day (RPD) for seven groups of different activities (i.e. vehicle rentals, scuba diving, snorkelling, kayaking, guided boat tours, boat rental and mudpool) is calculated for both high H and middle (M1 and M2)M seasons.

$$RH = RPDH * TH * OH \qquad\qquad (Eq.\ \text{1110})$$

$$RM1 = RPD\ M1 * T\ M1 * OM1 \quad RM = RPDM * TM * OM$$

$$(Eq.\ \text{1211})$$

$$RM2 = RPD\ M2 * TM2 * OM2 \qquad\qquad (Eq.\ 13)$$

TH is the total days of high season (July and August, 62 days), whereas OH is the occupancy rate during the high season, i.e. the proportions of activities occupied, and RH represent the revenue for high season. The middle season is also divided into two subgroups, as in the case of hotels, but considering different temporal distributions. The first subgroup considers only June (TM1 total days equal to 30) because the revenue is remarkably higher than the total of the rest of the middle season months. The second subgroup consists of April, May, September and October (TM2 total days equal to 122). OM1 and OM2 are the occupancy rate which is estimated as 90% and 40% in calculations for the first and second subgroups of the middle season, respectively.

TM is the total days for the middle season (April-May-June and September-October: 152 days) and the occupancy rate is set to 40%.
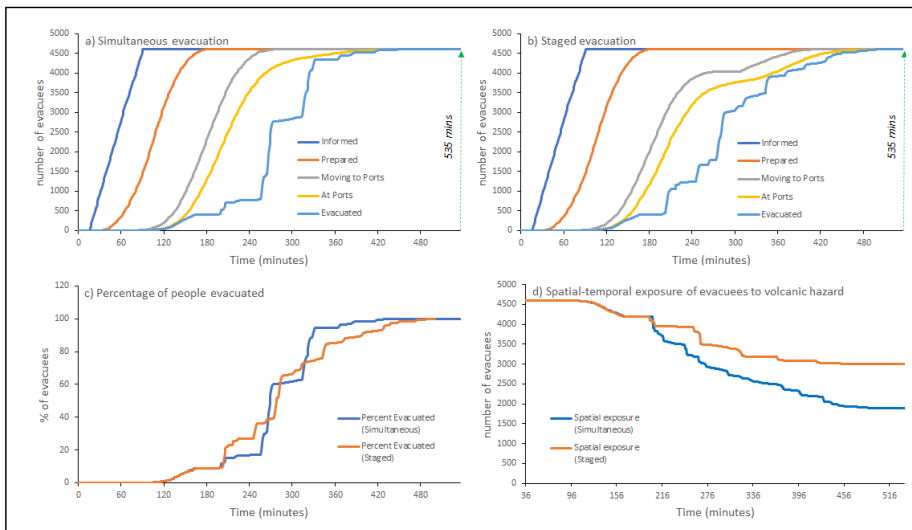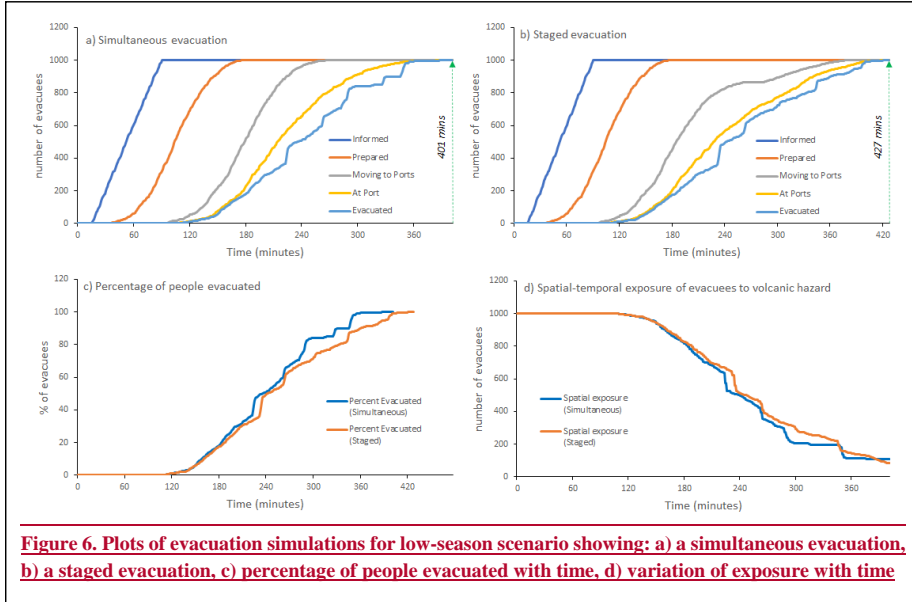
5 Results

5.1 Evacuation effectiveness

Figure 6. Plots of evacuation simulations for low-season scenario showing: a) a simultaneous evacuation, b) a staged evacuation, c) percentage of people evacuated with time, d) variation of exposure with time

Figure 7. Plots of evacuation simulations for high-season scenario showing: a) a simultaneous evacuation, b) a staged evacuation, c) percentage of people evacuated with time, d) variation of exposure with time.

Figures 6a,b and **7a,b** show simulation results for simultaneous and staged evacuations during low and high seasons, respectively. When considering evacuation time as a proxy for effectiveness, both simultaneous and staged evacuation scenarios are slightly faster during the low season (427(~6.7 and 401 minutes~7.1 hours, respectively) with respect to the evacuation during the high season (535

minutes(~8.9 hours for both). For the latter one, although both scenarios have equal evacuation times, their evacuation effectiveness differ (~~Figs~~Fig. **7c**). During the low season, a 95% evacuation
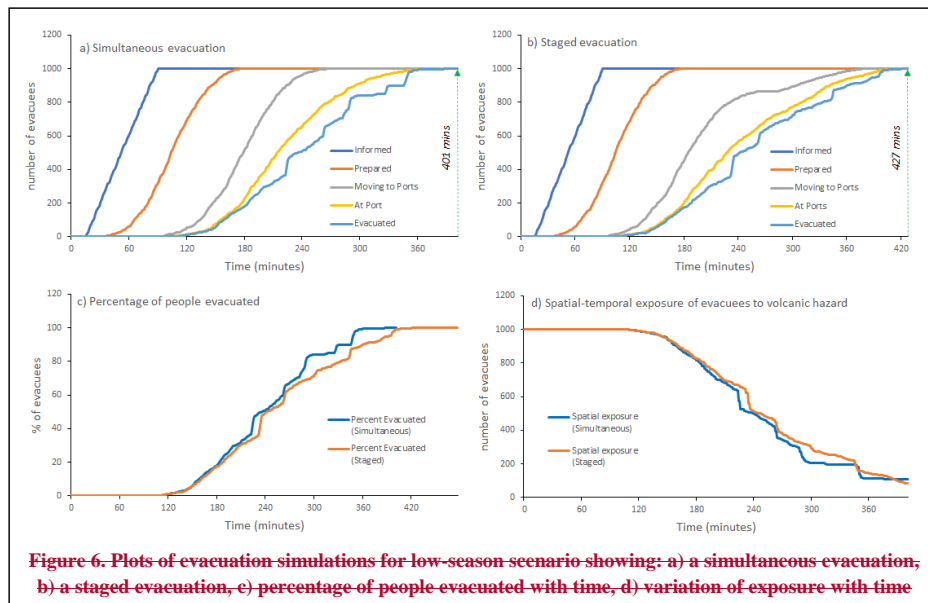
Figure 6. Plots of evacuation simulations for low-season scenario showing: a) a simultaneous evacuation, b) a staged evacuation, c) percentage of people evacuated with time, d) variation of exposure with time

effectiveness is reached within ~~348~~~5.8 and ~~392 minutes~~~6.5 hours for the simultaneous and staged evacuations, respectively (**Fig. 6c**). For the high season, a similar effectiveness is reached within ~~365~~~6.1 hours (simultaneous) and ~~447 minutes~~~7.5 hours (staged) (**Fig. 7c**). These results have two implications. Firstly, the simultaneous evacuation results in less people left exposed to increasing hazard over time, which confirms findings from previous studies (e.g., Chen and Zhan, 2008; Jumadi et al., 2019). Secondly, an increase of population of 360% of population between the low and high seasons results only in an increase in evacuation time of ~12%. In fact, assuming that warning time and preparedness time distributions are independent of population size, the main aspects that could impact the evacuation time are the pedestrian speed and the number and capacity of the ~~boats~~ferries used for ~~evacuations and the pedestrian speed.~~evacuation. For the case of Vulcano, ~~the relatively large capacity of the boats can equally accommodate the increase of population during the high season and~~ the pedestrian density in the roads considered under both scenarios does not impact pedestrian speed (the population density in the space, in our case roads, ~~increases beyond 1 person per square meter, which is not reached in Vulcano).~~increases beyond 1 person per square meter, which is not reached in Vulcano). In addition, the number and capacity of the ferries can equally accommodate the increase of population during the high season. If a larger number of people had to be evacuated (e.g., 10,000 people as supposed to 4,600), the time needed to evacuate 95% of the population would nearly double because of the number of ferries (10) and associated capacity (200 to 800 passengers) set in the simulation. However, 1,000

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people (considered in the low-season scenario) and 4,600 people (considered in the high-season scenario) can be almost equally managed by the capacity and number of ferries used.

5.2 Determination of revenue on Vulcano

	Revenues in Low Season (€)		
Business Activity	**1 Day**	**14 Days**	**31 Days**
Hotels	4,943	69,202	153,233

	Revenues in Low Season (€)		
Business Activity	1 Day	2 Weeks	1 Month
Hotels	4,943	69,195	148,275
Restaurants	1,119	15,666	33,570
TOTAL	6,062	84,861	181,845

Table 3 Revenues for each business activity during low season. 14 days are considered for two weeks, while for monthly calculations 30 days are considered.

With the methodology explained in section 4.3, the revenues from four different categories (hotels, hostels-B&Bs-residences;residence, restaurants; hotels, and leisure activities) are calculated. Hotels and restaurants are the only two categories providing revenues during low season (**Table 3**). While calculating the monthly revenue by using equations 6 and 10 the number of total days (TL) considered
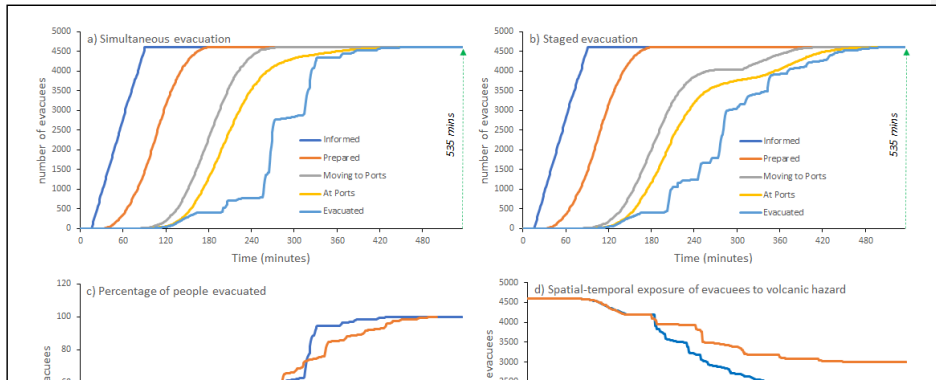
	Revenues in Middle Season (€)		
Business Activity	1 Day	2 Weeks	1 Month
Hotels	43,431	608,033	1,302,927
Hostel, B&B, Residences	7,112	99,561	213,345
Restaurants	14,960	209,440	448,800
Leisure Activities	4,067	56,936	122,005
TOTAL	69,569	973,969	2,087,077

Table 4 Revenues for each business activity during middle season. Two weeks represent 14 days, while 30 days are considered for a monthly calculation.

is 30 and the occupancy rate (OL) is set at 15%. With a monthly amount of 148,275about 153,233 €, the revenue from hotels is 4.54 times greater than the revenue from the restaurants during low season.

770 From the endbeginning of April, (beginning of middle season), the tourist population starts to increase on the island. Equations 2, 3 and 5 are used to calculate the monthly revenues from hostels-B&Bs-

	Revenues in Middle Season (€)		
Business Activity	**1 Day**	**14 Days**	**31 Days**
Hotels	30,310	424,340	939,610
Hostel, B&B, Residences	6,407	89,698	198,617
Restaurants	14,960	209,440	463,760
Leisure Activities	728	10,192	22,568
TOTAL	**52,405**	**733,670**	**1,624,555**

Table 4 Revenues for each business activity on Vulcano during middle season (April, May, June, September, October)

residences and restaurants. The number of total days (TM) for a month considered is 30 and theThe occupancy rate (OM) used for this season is 50%. On the other hand, while calculating monthly revenue for the middle season for hotels and leisure activities, an average is taken due to different occupancy

775 rates (OM) throughout the season. As seen in equations 8, 9, 12 and 13, the season is divided in two subgroups for these two categories. Thus, first the daily revenues are calculated for each month with designated values, e.g. forFor leisure activities 90% of occupancy is considered in June whereas 40% of occupancy is consideredfor September. Then, an average is taken to determine the daily revenue during middle season. After that, the number of total days (TM) considered to calculate the monthly revenue is

780 30., whereas 50% of occupancy rate is used for hotels. As seen in **Table 4**, hotels provide more than half (6258%) of the monthly revenue for middle season with a 1,302,927939,610 €, whereas the restaurants, hostels-B&Bs-apartments and leisure activities provide 22%, 1029%, 12% and 61% of the monthly revenue, respectively.

The touristic population reaches its peak point during July and August. Thus, the occupation rate (OH)

785 is considered 100% for all the categories. The total number of days (TH) for a month is taken as 31, i.e. representing July and August. The revenues are calculated by using equationsEquations 1, 3, 4, 7 and 1110. Hotels and restaurants providesprovide the highest revenue for this period with 44% and 46% of total revenue respectively, whereas leisure activities and hostels-B&Bs-residences contribute 4% and 6%, respectively (**Table 5**). While calculating revenue for low and middle seasons, table turn (TT), i.e.

	Revenues in High Season (€)		
Business Activity	**1 Day**	**14 Days**	**31 Days**
Hotels	174,985	2,449,790	5,424,535
Hostel, B&B, Residences	23,259	325,626	721,029
Restaurants	184,516	2,583,224	5,719,996
Leisure Activities	17,429	244,006	540,299
TOTAL	**400,189**	**5,602,646**	**12,405,859**

Table 5 Revenues for each business activity on Vulcano during high season (July, August)

the number of times a table is occupied by different groups, is considered 1. However, during July and August, restaurants are full of tourists and a table in a restaurant is served more than once. Thus, the number of TT varies for each restaurant while calculating the revenues for high season.

It should be noted that the prices for hotels, hostels-B&B-residences are not constant during different seasons, and, in fact, they slightly differ for each month. The highest prices throughout the year are

-	Revenues in High Season (€)		
Business Activity	1 Day	2 Weeks	1 Month
Hotels	174,985	2,449,790	5,424,535
Hostel, B&B, Residences	25,357	354,998	786,067
Restaurants	184,516	2,583,224	5,719,996
Leisure Activities	17,429	244,004	540,294
TOTAL	402,287	5,632,016	12,470,892

Table 5 Revenues for each business activity during high season. 14 days are used for two weeks and 31 days, representative for July and August, are considered for a monthly revenue.

applied for the second and third week of August which is considered as summer vacation in Italy. An average price for each season is calculated based on website data. Additionally, while calculating the revenues for each season, different occupancy rates are considered to obtain a range of revenues. For example, during low season it has been considered as varying between 5% and 15%. More thanrevenue for each season. About half (51%) of the yearly revenue

Business Activities	Revenues (€)
Hotels	16,202,583
Hostels, B&Bs, Residences	2,415,922
	13,882,881

Business Activities	Revenues (€)
Hotels	18,159,925
Restaurants	13,021,382
Hostels	2,638,859
Leisure Activities	1,690,616
TOTAL	35,510,782

Table 6 Total annual revenue for Vulcano Island resulting from hotels, restaurants, B&B's (including hostels and residences) and leisure activities

(35,510,78233,692,640 €) comes from hotels (**Table 6**). The other half is divided between the remaining three groups, with restaurants providing the second highest revenue after hotels with 37% of total revenue41% of total revenue. Even though in **Tables 3, 4** and **5** the monthly calculation is based on 31 days, the number of days considered in **Table 6** is related to each individual month.
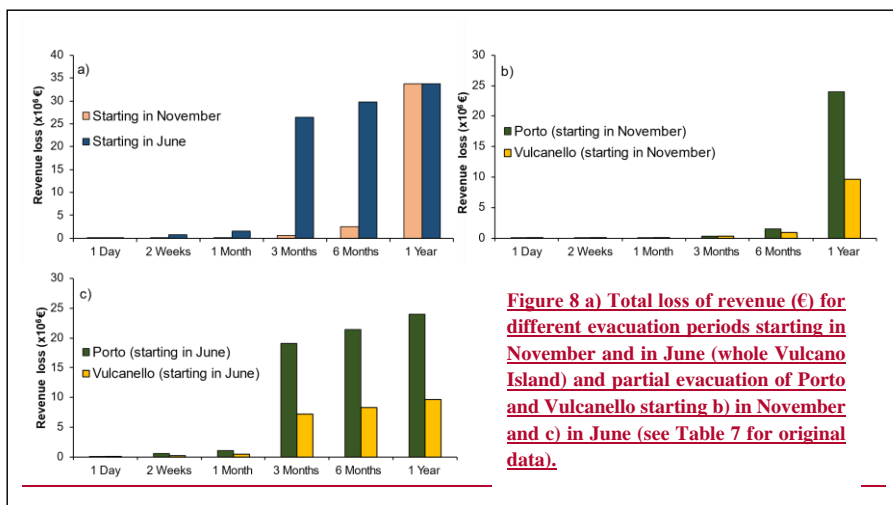
5.3 Analysis of potential economic impact of an evacuation

Evacuation	1 Day	2 Weeks	1 Month	3 Months	6 Months	1 Year
Total evacuation						
Starting in November	6,062	84,868	181,860	557,704	2,487,512	33,692,640
Starting in June	52,405	733,670	1,572,150	26,383,868	29,762,433	33,692,640
Porto only						
Starting in November	2,852	39,928	85,560	262,384	1,530,122	24,040,758
Starting in June	36,649	513,084	1,099,467	19,138,928	21,460,077	24,040,758
Vulcanello only						
Starting in November	3,210	44,940	96,300	295,320	957,390	9,651,882
Starting in June	15,756	220,584	472,680	7,244,940	8,302,356	9,651,882
Table 7. Loss of turnover related to tourism due to total or partial evacuation of Vulcano island (data based on Tables 3, 4 and 5)						

~~Figure 8a shows that the~~The evacuation results in a very different impact in the island's revenue whether it starts at the beginning or at the end of the tourist season. The total loss of revenue (expressed by the turnover) is significant if the evacuation begins in June and lasts for more than one month (i.e., > 1.5 million €; **Table 7, Fig. 8a**). If it starts in November, the impact becomes significant if it lasts more than 6 months ~~1 year~~ (i.e. ~~>30~~, >2 million ~~€).€;~~ **Table 7, Fig. 8a**). The high season represents the critical period. The impact of an evacuation starting in November and June in the two Vulcano main touristic areas (Porto and Vulcanello) is also considered (**Table 7, Fig. 8b,c8**). A partial evacuation of Piano was not considered because most of the tourist infrastructures are located in Porto and Vulcanello~~.~~ and, therefore, most of the turnover is related to activities in Porto and Vulcanello. Clearly the evacuation of only Vulcanello would result in a smaller loss of revenue with respect to a partial evacuation of Porto
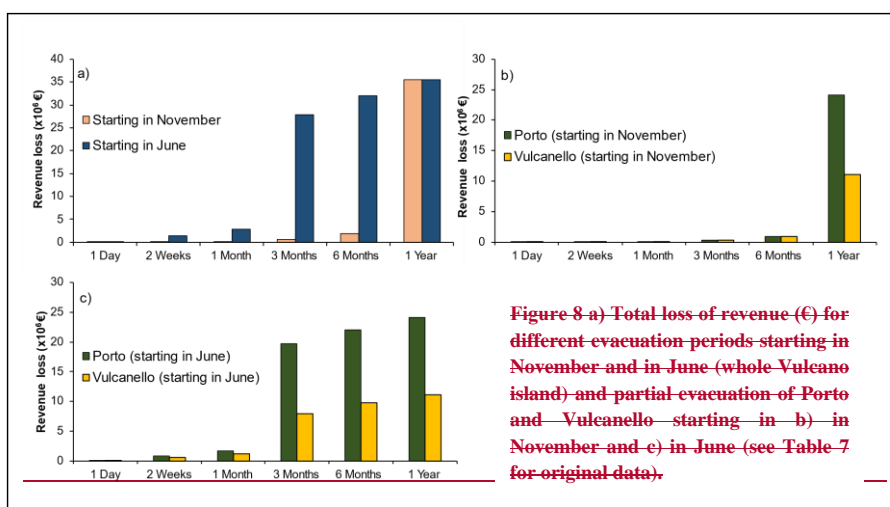

Figure 8 a) Total loss of revenue (€) for different evacuation periods starting in November and in June (whole Vulcano Island) and partial evacuation of Porto and Vulcanello starting b) in November and c) in June (see Table 7 for original data).

for any of the durations considered (i.e. ~~<15~~, <10 million ~~euros).€).~~ However, in the case of escalating

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unrest activity, the safety of people is typically prioritized with respect to economic factors. As a result, the areas that are the most exposed to the hazard (i.e., Porto) would be evacuated first.

Evacuation	1 day	2 weeks	1 month	3 months	6 months	1 year
Total evacuation						
Starting in November	6	85	182	545	1,945	35,525
Starting in June	99	1,393	2,885	27,827	32,023	35,525
Porto only						
Starting in June	58	819	1,654	19,694	22,055	24,142
Vulcanello only						
Starting in June	40	564	1,210	7,982	9,775	11,119

Table 7. Loss of turnover due to an evacuation (in 1,000 Euro)

Figure 8 a) Total loss of revenue (€) for different evacuation periods starting in November and in June (whole Vulcano island) and partial evacuation of Porto and Vulcanello starting in b) in November and c) in June (see Table 7 for original data).

6 Discussion

6.1 Effectiveness of evacuation

The main objective of our study is to provide decisions makers with an operational tool to investigate various evacuation scenarios. This evacuation simulation tool allows emergency managers to identify and optimize individual and organizational parameters (related to actions, behaviours, policies and resources) that minimize the evacuation time as crises evolve. The tool allows to estimate such key indicators as the minimum time necessary to fully accomplish the evacuation which, in the context of volcanic crises, can be compared to eruption forecasts provided by monitoring networks. Together, these two aspects provide a comprehensive picture of the various components to achievepursue successful emergency management.

However, although the overall evacuation time and the individual evacuation time are vital measures for enhancing the effectiveness of the evacuation process, they do not fully consider the dynamics of hazard and exposure during a volcanic eruption. In volcanic eruptions, hazard and exposure vary in time

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840 and space. In other words, the risk can increase because the probability of eruption might increase with time and because the actual exposure could be significantly higher a few hours after the evacuation order is issued compared to the first hour due to the movement of people towards the evacuation areas (e.g~.~., ports), which are sometimes closer to the source of the eruption (La Fossa) than where they initiated evacuation (e.g., Vulcanello). Therefore, to reduce exposure the goal should be to evacuate more people

845 faster (Han et al., 2007). The spatial exposure on Vulcano is complicated by ~~to~~ the proximity of the main port (Porto Levante) to La Fossa crater (i.e Porto Levante is located at the foot of the northwest flank of La Fossa). Particularly, for people in Vulcanello moving towards Porto Levante to evacuate requires that they get closer to the hazard source at La Fossa. ~~Evacuating people from these ports can, therefore, increase the exposure in time and space.~~ While optimizing evacuation requires that evacuees move away

850 from the hazard source, evacuation of people in the north side of Vulcano to either Porto Levante or Ponente cannot be done without moving people closer to the hazard source, especially when moving people to the Porto di Levante because it is closer to La Fossa than Porto ~~di~~ Ponente. Exposure could be reduced by moving people from the Porto di Levante area to Porto di Ponente, but the latter port cannot accept large ~~ships~~ferries nor handle large volumes of people. It is, in fact, significantly smaller and

855 characterised by shallower water than the port facility at Levante. Therefore, the planning of an effective evacuation should assess the evacuation time as well as the temporal variation of exposure. For the case of the two evacuation scenarios described above, exposure was assessed based on the distance from La Fossa volcano and was found higher for the staged evacuation (**Fig. 6d**) during both seasons, with an increasing difference over time during the high season (**Fig. 7d**).

860 Some assumptions have been made to carry out our evacuation simulations that should be mentioned: i) ~~people~~the evacuation starts before the eruption (so evacuation operations are not disrupted by volcanic hazards), ii) people are not allowed to return to the island after the alarm has been issued, ~~ii~~iii) people are only allowed to evacuate by foot ~~(~~for the sake of these simulations; however, ~~some people might try to drive to ports causing traffic jams~~a combination of evacuation strategies can also be considered in the

865 future (both by foot and ~~road blocks), iii~~motorized vehicles), iv) people with disabilities are considered in the simulations by using a low walking speed~~(~~; however, other considerations could be made in order to improve the analysis~~, iv) the "evacuation preparedness time" includes the time required to organize departure and secure the belongings that are left behind~~ (e.g~~. house, car(s), other~~., integrating evacuation with dedicated motorized vehicles~~, boats~~), v) people might be able to take with them small pets, vi)

870 animals of farming activities (e.g. goats, cows) are not considered here but represent a critical aspect for an island such as Vulcano, vii) evacuation is carried out from the three ports available on the island (i.e. Porto Ponente, Porto Levante and Porto Gelso) even though the only port that can be accessible by large ~~boats~~ferries is Porto Levante (more studies should be carried out based on the actual evacuation capacities of Porto Ponente and Porto Gelso, and in various weather and marine conditions~~). Finally~~),

875 viii) people follow the instructions provided in the evacuation orders (this is particularly important for staged evacuation as people in each community are asked to evacuate according to their turn; the

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possibility of having a fraction of the population not following the order of staged evacuation can be included in the simulations in order to add a level of uncertainty). In addition, while we did not directly include social vulnerability aspects due to small community size and lack of up-to-date data, the current evacuation simulation tool can be enhanced to include social vulnerabilities, especially if it is going to be used in larger and more complex social systems. The simulation can be parameterized based on more granular detail on socio-demographic characteristics of the agent population. This will allow to includeinclusion of social vulnerability factors related to age, health conditions, gender, language, education, access to resources and information in the evacuation simulation tool. Finally, it is important to consider and discuss some stochasticity and uncertainty aspects of the proposed evacuation simulation tool. Given that most of the distributions we have used to describe the various evacuation parameters are uniform, the stochasticity and uncertainty are relatively low, and the different simulations do not produce significantly different results. The main source of uncertainty in our model is related to the random distribution of population and capacity of the ferries. However, more parameters can be varied in order to explore a wider range of conditions.

6.2 Assessment of the economic impact of an evacuation of Vulcano island

The loss of revenue due to touristic business interruption associated with an evacuation of Vulcano Island is studied as a function of time, in order to investigate the influence of different touristic seasons, and as a function of space, in order to investigate how a partial evacuation affects the economic loss on the island. According to our results, both the time when the evacuation process is carried out and the duration of the evacuation period have significant impact on tourism. For instance, a short-term evacuation (i.e.,. up to three months) during low season (e.g.,. November, December to January) causes less than oneabout 0.5 million Euros€ of revenue loss (about 550,000 €).. Should peoplethe island be evacuated for 6 months, the loss could increase up to about 2.5 million € only after six months due to an overlap with the beginning of the middle season when touristic activities start to resume. One year of total evacuation on the island causes about 3534 million € of revenue loss. Only 52% of this loss results from evacuation during low season. (about 0.5 million €). This is due to the fact there are no tourists on the island during these months and most touristic activities ceasedstop. The situation is, therefore, critical if the evacuation needs to be carried out towards the end of the middle season (e.g.,. June) and/or during the high season when the population on the island reaches its peak point. In such a case, a month-long evacuation in June is almostabout 1 million € higher than 63 months of evacuation during the low season (i.e. starting from.. November to January). After that, a rapid increase in revenue loss is observed on the island: three months of evacuation starting in June causes up to 2826 million € of revenue loss which corresponds to 8078% of the one-year loss because it includes the high season.

InIt should also be considered that an evacuation during the low season could affect or compromise also the high season, due to the typical maintenance works of the touristic infrastructures performed during the low season and the impact on preparation activities (e.g., hotel booking). However, eruptions also

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attract tourists, as recently shown by the 2021 crises of Cumbre Veja (La Palma, Spain) and
Fagradalsfjall (Iceland). As a result, the overall impact on the high season revenue of an evacuation
during the low season due to an eruption of La Fossa would be difficult to forecast. Finally, in addition
to the high revenue loss that could occur during the high season, it is important to note that the evacuation
process becomes more complicated due to the high number of tourists between June and September (in
addition to the diversity of languages represented by international tourists and workers), whereas an
evacuation between November and April concerns only local people, all of whom would presumably
speak Italianmostly concern residents.

The loss of revenue on the island is also considered as a function of space. To do this, partial evacuations
including only Porto or only Vulcanello are evaluated. The main reason for assessing the partial
evacuation is to be able to maintain at least some activities on the island, without interrupting all tourism-
dependent businesses and also to see which part of the island has the highest impact on the economy.
According to our results, during the low season the loss of evacuating Vulcanello is slightly higher than
the loss of evacuating Porto (lower than a(<1 million euros).€). Although most of the touristic facilities
and all the restaurants are located in Porto, the largest hotels on the island are all situated in Vulcanello
and they are open for the whole year (Therasia Resort Seas and Spa and Jera Residence). However, with
the beginning of middle season the revenue loss in Porto exceeds Vulcanello. If the evacuation includes
July and August, the loss resulting from evacuating Porto is more than double of the loss of evacuating
Vulcanello.

Piano is not considered in the partial evacuation scenarios. In; in fact, on this southern side of the island,
there are no shops, hotels or any other leisure activities to attract tourists with the exception of a famous
lookout (Capo Grillo) and small beaches. Only two B&B's sBs and two restaurants are located in Piano
with revenues negligible revenue compared to those located in Porto and Vulcanello. However, this does
not mean that Piano has no effects on Vulcano's economy. As mentioned earlier, the wine factory is
situated between Piano and Gelso. According to the owner, the vineyard flourishes between March and
July. Thus, if an eruption occurs during this period and the area is evacuated, there willwould be at least
60,000 € of loss generating from Piano. AlsoIn addition, the important infrastructurescritical
infrastructure that areis not considered in the cost assessment of this study, such as the solar plant located
in Piano, may cause problems for other businesses. For example, if the electricity is cut on the island,
the restaurants and hotels cannot function and this affects directly the tourism and thus the revenues,
even though the evacuation is partial, and that part of the island is not affected.

Cost assessments are also required to conduct Cost-Benefit Analysis of different mitigation measures.
Although evacuating the island will cause an economic loss (i.e.., the loss of revenue as the cost), it is a
key measure to reduce the impact on public health. It helps ensure the prevention of eruption related
injuries and deaths, hence the main components of benefits. Quantifying the value of life is an ethical
issue. Although there are studies that try to assign a value to a human life (e.g.., Cropper and Sahin,
2009), here we do not consider it, as this is beyond the scope of our analysis. In any case, if an eruption

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on the island is imminent, total and/or partial evacuations will be conducted regardless of the cost in order to avoid casualties. However, it is important to evaluate the socio-economic impact on affected communities for authorities, in order to help them to implement informed decisions.

Although this study has provided some significant findings on the tourist sector of the economic system of Vulcano Island, such as the main income activities and the possible loss in case of an evacuation, it does not provide a complete picture for the cost assessments, and some important caveats need to be discussed. The first and the most important limitation concerns the lack of data. Although the municipality of Lipari was visited in May 2014, no access was granted for any official data concerning the economic situation of the Aeolian Islands, let alone Vulcano itself. All the data used to calculate the revenue on the island were based on our field visit in May 2014, official websites and various booking websites were used to complete the data set. Another important point to mention is that the main focus of our study is on the ~~revenues~~revenue originating only from tourism-related businesses, and, therefore, the total cost of evacuation process is not investigated (i.e~~.~~., cost of evacuation operations and of relocating people). This loss presents only one part of the total cost associated with an evacuation. An extensive cost assessment requires the consideration of all different types of costs involved with the evacuation process.

~~**6.3 Potential negative and positive economic consequences of a volcanic crisis**~~

~~Forecasting volcanic eruptions and managing volcanic crises presents an important challenge for both scientists (e.g. geochemists, geophysicist, geologists, volcanologists) working in observatories and civil authorities such as those associated with emergency management. In Italy, the Civil Protection Department play an active role in decision making. Based on the combination of monitoring parameters provided by the INGV and dedicated Competence Centers and background data available for the event that might occurre at Vulcano, the Civil Protection Department declares the alert levels in close collaboration with the Regional Civil Protection authorities. The evaluation is based on the reports of the phenomena and on the evaluations of hazard made available by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and by the Consiglio Nazionale delle Ricercheof Italy – Institute for electromagnetic sensing of the environment (CNR-IREA).~~

~~However, many impediments may be encountered in interpreting key aspects such as~~**6.3 Recent unrest on Vulcano and implications for crisis management**

Starting from August-September 2021, analysis of the monitoring data at Vulcano island showed an increase in the concentration, flux and temperature of volcanic fumaroles at the crater area, an expansion of the emission areas, and an increase in low-energy seismicity. Satellite and ground deformation analysis also showed an uplift in the summit area of the volcano of about 1 cm. These phenomena caused the Italian Civil Protection Department to raise the alert level on 1 October 2021 from "GREEN - Quiescence" to "YELLOW - Minor Shallow Hydrothermal Crisis". Resulting operational actions carried out on the island as a result of this change in alert level included i) the strengthening of the monitoring

activities, ii) the constant communication between the scientific community and the operational structures of the Italian Civil Protection Department, and iii) the update of the civil protection plans at different territorial levels (Municipal, Regional and National).

At local level, the Mayor of Lipari formalised the new municipal civil protection plan for volcanic risk on the island of Vulcano in November 2021. Moreover, due to the increase in gas emissions from the ground, which represents a hazardous event with local impact, overnight stays in the Vulcano Porto (Porto) and adjacent areas were prohibited, through the issue of a special order, as of 22 November 2021. Non-residents were also banned from entering the island and the use of self-protection measures was recommended (e.g., ventilation of buildings, limited use of basements, avoiding areas of gas emissions, monitoring of health conditions, pay attention to communications from the municipality). Since mid-December 2021, the monitoring parameters have shown a gradual stabilisation on high values, so that some mitigation measures at local level have been lessened through the issue of specific order of the Mayor of Lipari. On 24 December 2021 residents were allowed back to Porto area also during the night, with the exclusion of vulnerable people (citizens with reduced mobility and / or respiratory diseases), and CO_2 concentration values are constantly monitored in order to inform the population. On 1 February 2022 also non-residents were allowed back to the island even though some critical restrictions remain (e.g., no access to potentially hazardous areas such as the La Fossa volcano and the beach in Porto Levante, exclusion of vulnerable people to sleep in the whole Porto area).

At national level, the Decree of the Head of the Italian Civil Protection Department of 6 December 2021 formalised the technical group for environmental monitoring of volcanic gas and air quality to complement routine volcanic monitoring, which includes representatives of public health, environmental, volcanology and civil protection organizations. On 7 December 2021, the National Civil Protection Plan for volcanic risk on the island of Vulcano was formalised. The Plan, compiled by the Italian Civil Protection Department in agreement with the Regional Department of Civil Protection of the Sicilian Region, the Prefecture-Territorial Office of the Government of Messina and the Municipality of Lipari, defines the mitigation actions that all the stakeholders involved in the emergency management must take and foresees the evacuation of the population before the eruption onset in case increasing volcanic unrest is observed. The results of the work presented in this paper as well as the insights into risk assessment presented in Bonadonna et al. (2021) were used to finalise the emergency plan at national level. However, given that the recent unrest was mostly related to gas hazard and was, therefore, managed at the local level (i.e., by the Municipality) and that the overnight restrictions issued by the municipality did not involve an evacuation of the island, the results of these two analyses could not be tested nor validated.

i) whether or not unrest will lead to an eruption, ii) the nature of explosive activity (magmatic or hydrothermal), iii) the eruptive style (i.e., effusive, explosive or both), iv) the potential activation of lateral vents, v) the eruption magnitude (i.e. erupted volume) and intensity (i.e. the rate of discharge of magma, plume height), vi) the type, extension and timing of hazards with the potential to impact human

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1025 life and the infrastructure supporting evacuation whether occurring either in the unrest phase or eruptive phase or both. The interpretation of scientific data complicates the decision-making process for the officials (Fearnley, 2013). Higher levels of scientific uncertainty may thus translate to increased difficulty for emergency managers to understand the value of evacuation (measured in terms of human lives saved) and the costs associated with any evacuation that is not accompanied by the occurrence of

1030 hazards necessitating eruption.

When a volcano begins to show increasing signs of unrest above background level, authorities have to deal with uncertainties and decide how to manage a potential crisis (e.g. have people shelter in place or evacuate some or all of the population), as scientists cannot guarantee if the unrest will result in an eruption or not. Although successful forecasts have been made (e.g. Mt St Helen's 1980, USA; Mt

1035 Redoubt 1989-1990, USA; Pinatubo 1991, Philippines), false alarms that cause both scientists and officials to lose credibility also occurred in the past (Sparks, 2003; Tilling, 2008). For example, during 1983-1985 volcanic crisis at Rabaul Caldera (Papua New Guinea), the government practiced many evacuation exercises, which led to voluntary evacuations by villagers. They intensified disaster preparedness activities when intense earthquake swarms begin to occur in September 1983 and

1040 continued until April 1984. Although there was a high expectation that an eruption was imminent (i.e. that eruption would take place) by early 1984, the number of earthquake swarms and their intensities suddenly decreased. The government subsequently dropped the alert level in November 1984 and by mid-1985 the seismicity returned to its pre-1983 levels (Hastings, 2013). Consequently, the volcanic crisis resulted in substantial losses of revenue due to business interruptions with the total cost of

1045 emergency preparations exceeding 20 million PNG Kina (~ 21 million $). At the end, many people thought that two years of preparation was a waste of money (Hastings, 2013). Nevertheless, some benefits also emerged from this crisis, as public awareness of potential volcanic hazards increased and the community became more resilient (Hastings, 2013; Tilling, 2008).

Unfortunately, successful forecasts followed by evacuations may also cause economic distress for

1050 communities located in hazardous areas. As an example, in October 1999, almost 19,000 people were evacuated from Baños, Ecuador when Mt. Tungurahua renewed activity after a long period of quiescence. Some 95% of the community's economic activity was dependant on tourism (Lane et al., 2003), showing a similar situation to Vulcano Island. After the evacuation, an economic crisis was felt both locally and nationally. In the city of Ambato, where evacuees were rehoused, unemployment was

1055 an issue, health costs increased by about 103%, and food and beverage prices increased by about 108% (Lane at al., 2003). When authorities realized that economic recovery would be hard without tourists, the tourism industry launched an effective campaign to promote positive views of the area by using the volcano's attractiveness, to convince both domestic and foreign tourists that the situation in Baños was back to normal. Even journalists were invited to the town to report on the successful recovery (Lane et

1060 al., 2003). Finally, in 2000, Baños attracted approximately 23% of the country's 615,000 foreign visitors. In November 2001, 56% of all tourists visiting Baños were foreigners (Lane et al., 2003).

As seen in both cases at Rabaul and Baños, a volcanic crisis, if not managed well, can easily result in an economic crisis, with or without an evacuation and an eruption occurring. This is also valid in the case of Vulcano Island. Even without an evacuation order, the increasing level of unrest may cause the local people to leave the island, if they believe that tourism on the island may be affected negatively by the increasing volcanic activity. This is especially true since most business owners are not from Vulcano and they may decide to relocate their activities. In both cases, the economy of the island would be negatively impacted. Additionally, there could be significant negative economic impacts on Vulcano associated with changes in the volcano alert level even when an eruption or evacuation does not occur, as Peers et al. (2021) described for the protracted unrest at Long Valley Caldera, California, in USA. Volcanic unrest and eruptions can also have positive impact on economy. As an example, volcano tourism and geotourism has become more and more popular all around the world. It is estimated that between 150 and 200 million people visit volcanic and geothermal environments on an annual basis (Heggie, 2009; Erfurt-Cooper, 2011), because a growing number of tourists seek adventure by planning holidays close to active volcanoes (Brace, 2000; Erfurt-Cooper and Cooper, 2010). As an example, in 2008, 1.2 million tourists visited the active volcanic features in Hawaii Volcanoes National Park, 3 million visited the geysers and hot springs of Yellowstone National Park and in 2004 103 million people visited Fuji-Hakone-Izu National Park in Japan (Heggie, 2009; Erfurt-Cooper, 2011). Other than USA and Japan, geothermal and volcanic activity in Italy and Iceland are also highly attractive destinations for tourists (Heggie, 2009). Research by Bird et al. (2010) in Thorsmork, Iceland near Katla Volcano in 2009 examined the relationship between tourism and volcanic activity. They found that all the participants (tourists) knew that Iceland is volcanically active, but they do not think of volcanic eruptions as hazardous events, hence they lack hazard knowledge. Additionally, most tourists and tourism employees think that tourism will benefit positively after a future Katla eruption. However, according to results of Dominey-Howes and Minos-Minopoulos in 2004 in Santorini, Greece, it is the residents who fear that a future eruption may have a negative impact on the tourism.

Vulcano Island appeals to a wide range of tourists: some visit to relax and/or for health reasons, whereas others are attracted to volcanic landform and geothermal features. Thus, an increase of unrest may attract more adventure-driven tourists, unless such visits are curtailed by civil authorities as a result of increased likelihood of eruption and resulting limitation of the number of people on the island. If the increasing activity on the island results in an evacuation and finally in an eruption, still many tourists interested in natural areas and adventure may want to visit the island once the activity is back to pre-eruption and the risk is decreased. This type of tourism should be foreseen and well organized to boost the local economy especially after business disruption due to evacuation and/or eruption.

7. Conclusions

Evacuation is often the only strategy to save lives in case of extreme volcanic activity and rapidly escalating unrest. This is especially critical for La Fossa volcano whose activity has been

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~~characterized~~characterised by hydrothermal events, which are typically very sudden and unpredictable, and magmatic events with little warning signals (e.g~~.~~, 1888-90 Vulcanian cycle). In such a case and considering the high level of population exposure to dangerous hazards, evacuation ~~should~~might be considered even in case of weak unrest. Nonetheless, the timing and routing of evacuation is critical to remove people from ~~the hazardous zone~~hazard zones before ~~it is~~they are impacted.

The Vulcano ~~evacuation simulation tool~~Evacuation Simulation Tool decribed here has been developed to test the effectiveness of ABM simulation in evacuation planning for areas subject to volcanic hazards on a small island. Based on a pre-eruption simulation at Vulcano, ~~we have demonstrated that the~~both the simultaneous and the staged evacuation are slightly faster during the low touristic season ~~(401~~(~6.7 and ~~427 minutes~~~7.1 hours to evacuate 1,000 people, respectively; **Fig. 6a,b**) with respect to the high touristic season ~~(535 minutes~~(~8.9 hours to evacuate 4,600 people; **Fig. 7a,b**). Nonetheless, we have also shown that the type of evacuation (i.e~~.~~, staged or simultaneous) can optimize the number of people evacuated in time, with the simultaneous evacuation being more efficient at removing people from the island than the staged evacuation~~, especially in the~~. In fact, after 5 hours (300 minutes), during low season, about 84% and 72% of people would be evacuated with a simultaneous and a staged evacuation, respectively, while after ~6 hours (370 minutes), during the high season, about 96% and 86% would be evacuated with a simultaneous and a staged evacuation, respectively (**Figs. 6c and 7c**). Additional analyses should be carried out to explore more ~~evacuations~~evacuation conditions (e.g~~.~~, evacuation by car, evacuation from fewer ports, evacuation after the onset of the eruption) ~~or~~and the role of social vulnerability. In fact, the proposed evacuation simulation tool can be used to model varying impacts for different scenarios to enable proper allocation of resources required for evacuations and economic support of the affected areas.

We have also shown how, in an island ~~as~~like Vulcano whose economy is based on tourism, the timing and duration of evacuation can have a very different ~~impacts~~impact. In fact, if the evacuation of the whole island starts ~~in~~at the ~~low~~beginning of the low touristic season (e.g., November), the impact becomes significant only if it lasts more than 6 months~~1 year~~, (> 7% of annual total turnover), whereas if it starts in June (i.e., at the end of the middle season and approaching the high touristic season in July-August) the impact becomes significant after 1 month (> 5% of annual total turnover) and reaches 78% of the annual total turnover after 3 months. ~~In particular, our~~Our results also show that a total evacuation starting in June~~, for a period of 6 months or less, result~~ of various durations results in ~~~95~~88-98% more revenue loss than ~~the~~an evacuation starting in November. This is directly related to the large number of ~~high tourist population~~tourists on the island during ~~that period.~~the high season (July-August). In addition, ~~if the~~an evacuation ~~starts in November and lasts for~~of up to ~~6~~3 months~~, there is no~~ in the low season would not produce a large difference in revenue loss between the partial evacuations of Porto and of Vulcanello in terms of revenue loss. On the contrary, ~~if the~~an evacuation ~~starts in June instead~~ of ~~November, the revenue loss resulting from evacuating~~Porto ~~is 30-50~~of 1 year would cause 60% higher ~~than evacuating Vulcanello. Moreover, for an evacuation lasting more than 6 months (e.g. one year), the~~

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result of evacuating Porto causes 50% of higher revenue loss than evacuating Vulcanello. Consequently, we can say that for a partial evacuation, evacuating Porto starting from June will cause the largest impact on the island's economy. This is due to the fact that all leisure activities and restaurants with the majority of hotels, hostels and B&B's Bs are located in Porto. However, it is important to stress that human life

1140   has to be prioritized over economic losses, therefore being the most exposed area to volcanic hazard, Porto should be evacuated even though it is Regardless of the beginning of the evacuation and associated with the highest revenue losses. Finally, regardless of the timing of the evacuation and its duration, the total evacuation of the island generates 30-50 would generate 28-53% more revenue loss than the partial evacuation of Porto, and 45-70 47-73% more revenue loss than the partial evacuation of Vulcanello.

1145   It is important to stress that, during crises, human life is prioritized over economic losses, whatever the situation. However, our analysis provides insights into the potential economic impact, which could be mitigated if foreseen and integrated into an emergency plan.

Appendix A

Vulcano ~~evacuation simulation tool~~Evacuation Simulation Tool setting page and interface
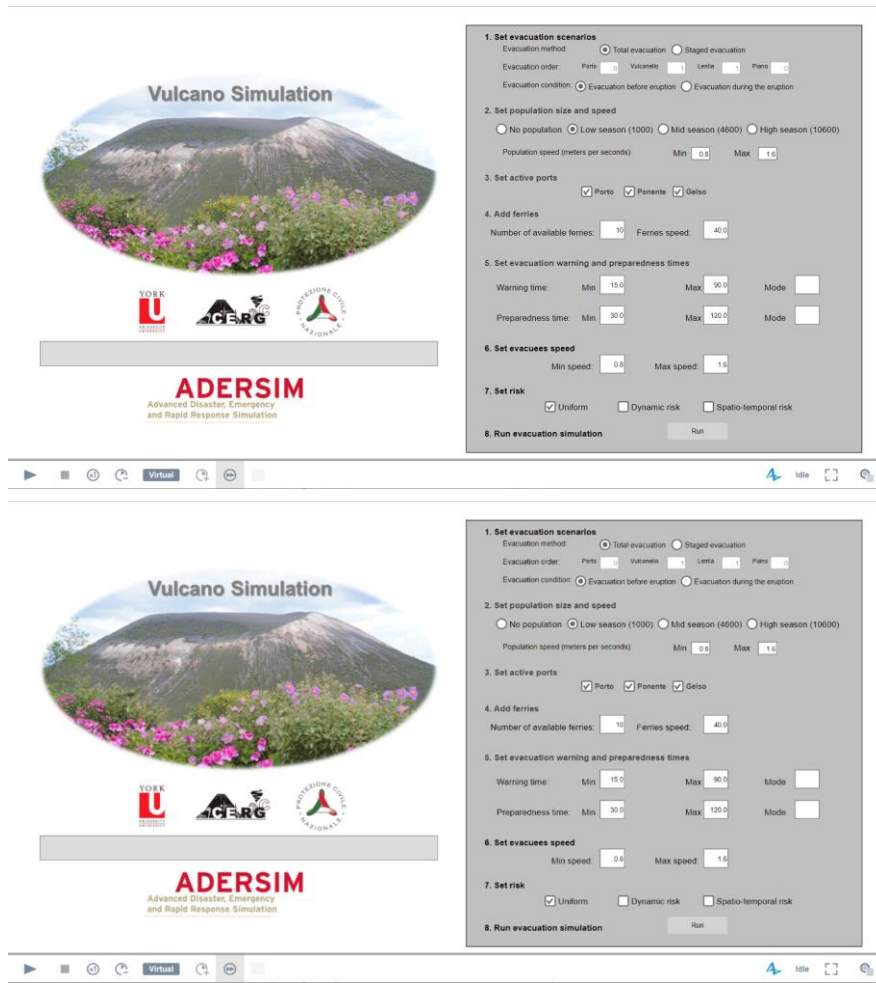
Figure A1 Parameter and scenario setting page of the Vulcano ~~evacuation simulation tool~~Evacuation Simulation Tool
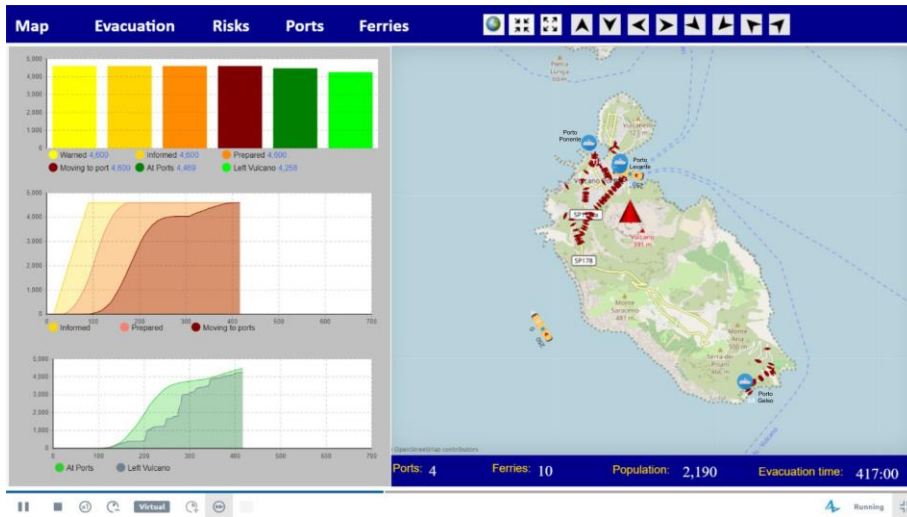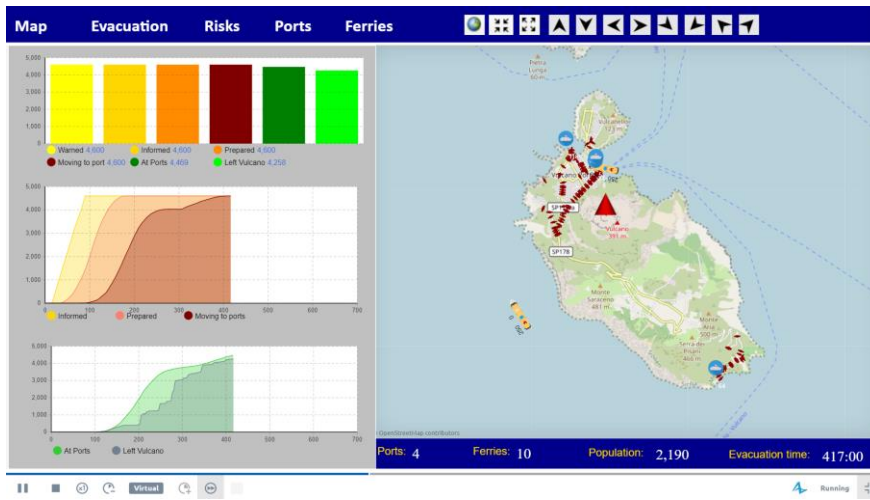
1160   **Figure A2 Main interface page of the Vulcano** ~~evacuation simulation tool~~**Evacuation Simulation Tool**

Appendix B

Example of a pedestrian evacuation simulation run (video)

An example of a pedestrian evacuation simulation run for a simultaneous evacuation scenario during high season on Vulcano (~~4600~~4,600 people consisting of 400 people in Piano, 400 people in Vulcanello and ~~3800~~3,800 people in Porto; see main text for details) can be found at this link: ~~http://gofile.me/5ri20/GrlDLHsPQ~~
http://gofile.me/5ri20/GrlDLHsPQ

The simulation shows movement of evacuees from different parts of the island to their designated or nearest active port from where they will be evacuated by ferry (Porto Levante, Porto Ponente in the North and Porto Gelso in the South). Yellow colour represents people who have received the evacuation order, orange colour shows people who are preparing for evacuation, and brown colour shows people who are moving towards the ports. Bar at the bottom shows the number of ports and ferries used (in this case 3 ports on Vulcano and 1 port in Milazzo where ferries bring the evacuated people), the number of people at a given time step and the evacuation time indicated in minutes.

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Declarations

1190 **Availability of data and materials**

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

C.B., A.A., F.R., T.Z. and C.F. have conceived and written the first draft of the manuscript. A.A. has developed the ABM tool and performed the simulations for different evacuation scenarios based

1195 on information provided by C.B. and C.F.. T.Z. has carried out the data collection and analysis necessary to the assessment of economic impact of an evacuation of Vulcano under the supervision of F.R., C.B. and C.F.. C.C., M.R., C.E.G., S.B., S.M., M.P. and A.R. have provided key insights into interpretation of the results. All authors have contributed to the finalisation of the manuscript.

Competing interests

1200 The authors declare that they have no competing interests.

Disclaimers

The information set out in this publication reflect the author's views.

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