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Impacts to agriculture and critical infrastructure in Argentina after ashfall from the 2011 eruption of the Cordón Caulle volcanic complex: an assessment of published damage and function thresholds

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Abstract

The 2011 Cordón Caulle (Chile) was a large silicic eruption that dispersed ashfall over 75,000 km^2 of land in Central Argentina, affecting large parts of the Neuquén, Río Negro, and Chubut provinces, including the urban areas of Villa la Angostura, Bariloche and Jacobacci. These regions all received damage and disruption to critical infrastructure and agriculture due to the ashfall. We describe these impacts and classify them according to published damage/disruption states (DDS). DDS for infrastructure and agriculture were also assigned to each area using the tephra thickness thresholds suggested by previous studies reported in the volcanological literature. The objective of this study was to evaluate whether the impacts were as expected based on the DDS suggested thresholds, and to determine whether other factors, apart from ashfall thickness, played a part. DDS thresholds based on tephra thickness were a good predictor of the impacts that occurred in the semi-arid steppe area around Jacobacci. This was unexpected as the more severe impacts were related to the challenging environmental conditions (low precipitation levels, high levels of wind erosion) and the daily wind remobilisation of ash that occurred, rather than the ashfall thicknesses received. The temperate region, including Villa la Angostura and Bariloche, performed better than the DDS assigned by ashfall thickness suggested. Despite deposits as thick as 300 mm, full recovery occurred within months of the ashfall event. The DDS scales need to incorporate a wider range of system characteristics, and environmental and vulnerability factors, as we propose here.

Keywords: Volcanic ash, Puyehue-Cordón Caulle, Ashfall, Ashfall Impacts, Infrastructure, Agriculture

Introduction

Volcanic ashfall is commonly the most widespread hazard to occur after an explosive eruption (Dingwell et al., 2011). Ashfall can be highly disruptive and potentially damaging to many sectors of society, including critical infrastructure and agricultural systems, due to its abrasive, corrosive and conductive potential. This means that the likely impacts of an ashfall event need to be well understood and planned for in order to minimise disruption and damage (Wilson et al. 2012a).

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The use of risk and impact modelling in order to better estimate impacts means that there is a growing need for accurate vulnerability information, which can be combined with hazard information to provide input data for the risk and impact models. Risk modelling quantifies the likelihood of impacts occurring using a probabilistic hazard model (ISDR 2009). In contrast, pre-event impact assessments (pre-EIA) predict the impacts from an event but do not have numerical probabilities attached to them. These both require information about the susceptibility of a specific system to the impacts, which may be captured by a vulnerability assessment (Wilson et al. 2014a). Impact and associated vulnerabilities can be assessed by empirical (observations, previous case studies) and analytical (simulations, experiments) approaches. A method commonly applied after an ashfall event is post-event impact assessment (Post -EIA) which assess empirically or analytically the impacts on exposed societal elements (e.g., water and power supplies and agricultural production), as well as the hazard (e.g., ashfall thickness/loading, grainsize, surface chemistry) and vulnerability characteristics (e.g., infrastructure design, farming style, access to mitigative measures) that influenced the impact. Numerous impact assessments have been conducted after ashfall events, focussing on the impacts to critical infrastructure, electricity systems, water systems, and agriculture (for a list of post-EIA see Wilson et al. 2014c).

Damage or disruption states (DDS) are a method of summarising and organising impact data during post-EIA, and predicting impacts in pre-EIA and risk assessments (Blong 2003a). These states use a common scale and have qualitative indicators assigned to each level, allowing for observational data to be placed on a numerical scale (Blong 2003b). Additionally, average expected or observed hazard intensity metrics (usually ashfall thickness) have been assigned to many DDS schemes, in order to allow for the prediction of what DDS is likely to occur at a given hazard intensity (Jenkins et al. 2014; Wilson et al. 2014a). This means DDS can be employed in pre-event impact forecasting in conjunction with hazard models. This usage requires some assumptions, as DDS do not take into account other measures of hazard intensity (e.g., ashfall thickness, loading, grain size, surface chemistry), existing vulnerabilities of system designs (e.g., type of systems, areas where components are exposed to ashfall), or mitigation measures (e.g., cleaning equipment, specific systems designed for ashfall resilience) that may be in place. Volcanic ash DDS schemes are typically focused on the characteristics of the hazard and have limited if any acknowledgement of the range of vulnerability characteristics that may influence impacts to the exposed societal elements that are being assessed. The small number of well-documented case studies available, and the inconsistent level of detail between different case studies also limit available schemes. Additionally, many DDS have been developed from specific case studies of an eruption or for a particular application, with little reflection on their utility in a broader application. Yet with increasing use of volcanic hazard DDS schemes, including at regional and global scales (e.g. Jenkins et al. 2014) the review of their predictive capacity is appropriate and necessary.

Ashfall from the 2011 Cordón Caulle Volcanic Complex (CC-VC) eruption affected large areas of the Argentinian provinces of Neuquén, Río Negro, and Chubut (covering 75,000 km^2) (Buteler et al. 2011), and thus presented an opportunity to assess the impacts at different ashfall thicknesses, and draw comparisons with previous case studies. In this study we will:

- Assess and qualitatively describe the impacts to critical infrastructure and agriculture after the eruption.
- Categorise the interview data collected using a range of DDS schemes (e.g., Jenkins et al. 2014; Neild et al. 1998; Wilson et al. 2014a; Wilson et al. 2009).
- Assign the same DDS based on the ashfall thicknesses received.
- Compare the DDS assigned to areas based on the qualitative data collected during post-EIA to the DDS assigned based on the ashfall thickness thresholds given to each by their authors.

This assessment allows of whether impacts were as expected given the hazard intensity experienced, and provide insight into what vulnerabilities, system design factors, and mitigation measures may have caused any differences.

Background

2011 Cordón Caulle eruption

The eruption sequence began with a swarm of volcano-tectonic earthquakes detected under the volcanic complex on 27 April 2011 (OVDAS-SERNAGEOMIN, 2011). These earthquakes continued to increase in magnitude and frequency until June 4th when the eruption sequence began with a series of Plinian phases (Schipper et al. 2013). A 5 km wide ash and gas plume rose to 12.2 km height. While lava was not initially observed, pyroclastic flows were noted. Eruptive activity continued throughout June and into July. Ash and gas plumes continued to erupt up to 13 km high. Ash particles were detected on air quality monitoring filters in Porto Alegre, Brazil, over 2000 km to the northeast of the vent, on 9 and 14 June (de Lima et al. 2012). Long-range transport of the ash plume led to flight disruptions in New Zealand, Australia and South Africa in late June and early July (Smithsonian 2014). Prior to 2011, the last eruption from this centre was in May 1960, 38 h after the main shock of a M9.5 earthquake in Valdivia, Chile (Smithsonian 2014).

Study area

This study focussed on the impacts due to ashfall within the Northern Patagonia regions of Chile and Argentina. Within the study area were two distinct environmental zones: the Villa la Angostura, Parque Nacional Nahuel Huapi (Nahuel Huapi National Park), and Bariloche areas (including the Chile-Argentina border) and the steppe region (including Jacobacci and the Comallo Valley), Argentina (Fig. 1). The Nahuel Huapi National Park is a temperate, highland climatic area (Peel et al.

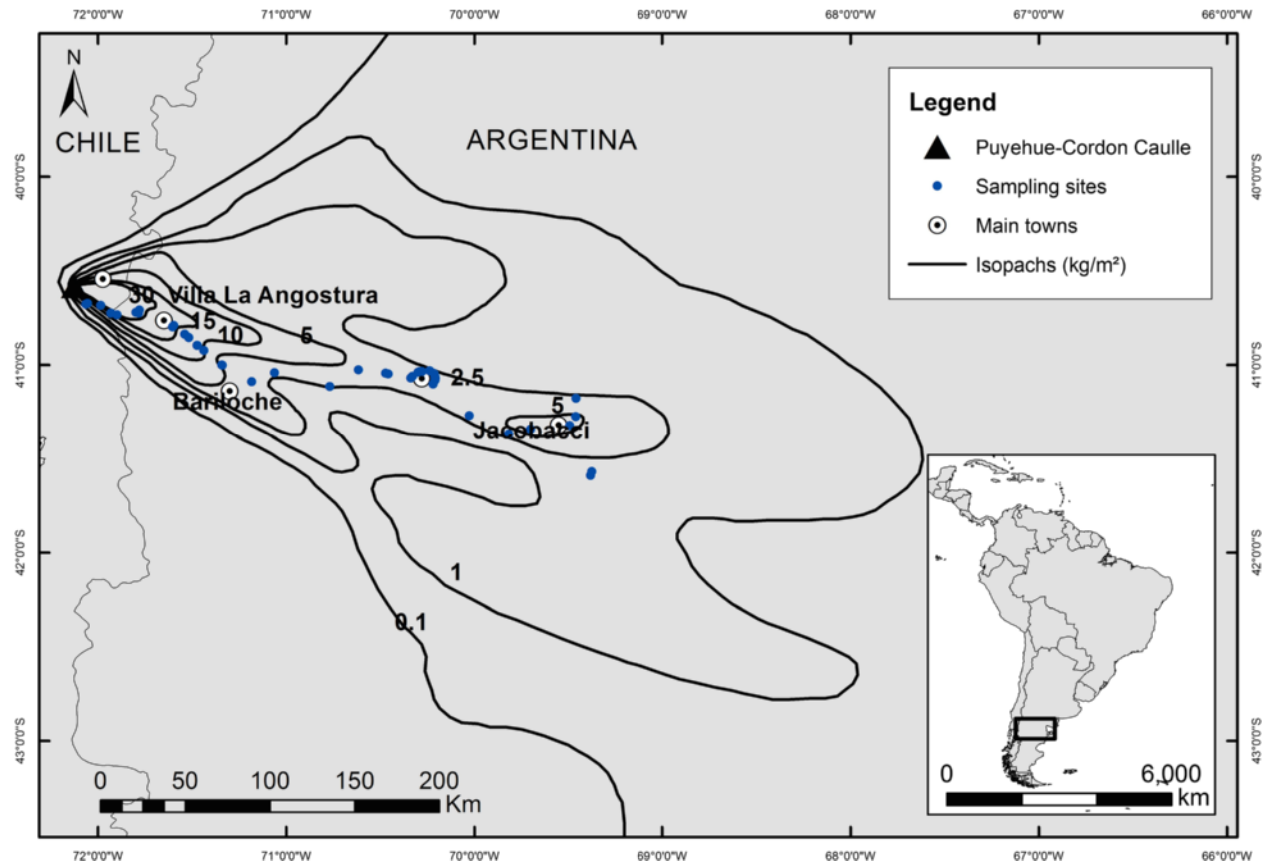

Fig. 1 Map of ash isopachs (adapted from Collini et al., 2012; converted to fall depth in mm, using 0.5 g/cm^2 average density (INTA 2011)) from 4 June 2011 eruption of PCC-VC and main population centres affected. Interview and sampling sites visited by research team are shown as blue dots

2007), that receives between 800 and 4000 mm of precipitation per annum (Servicio Meteorologico Nacional, 2012). In contrast the semi-arid steppe and Jacobacci (Peel et al. 2007), receives less than 300 mm precipitation per annum (Salazar et al. 1982). However, in the 6 years prior to the ash fall, rainfall levels were much lower than this (<160 mm/year) leading to regional drought conditions (Departamento Provincial de Aguas 2011). The three main population centres of Villa la Angostura, Bariloche, and Jacobacci (Table 1; Fig. 1) were affected by varying thicknesses of ashfall (Fig. 2).

Damage/disruption states

The most widely applied DDS scales for critical infrastructure impacts are taken from Wilson et al. 2014a, and Jenkins et al. 2014. Each of these scales was developed using a combination of previous case study data, empirical information, and expert elicitation. For agricultural impacts, the most detailed agriculture-specific DDS system is outlined in Jenkins et al. (2014). These are based on previous experimental and theoretical studies and were compiled as part of the UN-ISDR Global Assessment Report on Disaster Risk Reduction.

Table 1 Characteristics of towns in the study area and ash exposure from 2012 PCC-VC eruption

Town	Population (at 2010 census)	Depth of ash fall (mm)	Distance from PCC-VC	Description
Villa la Angostura	11,063	150–170 mm	54 km ESE	Located in a temperate zone towards the northern end of Lago Nahuel Huapi. The town experiences strong seasonal increases in population due to influxes of tourists. Its economy is based on tourism.
San Carlos de Bariloche	112,887	30–45 mm	~100 km SE	Bariloche is located on the southern shore of Lago Nahuel Huapi.
Ing. Jacobacci	6,261	~50 mm (fine ash sized)	240 km ESE	Located on the semi-arid steppe. Primarily an agricultural service town.

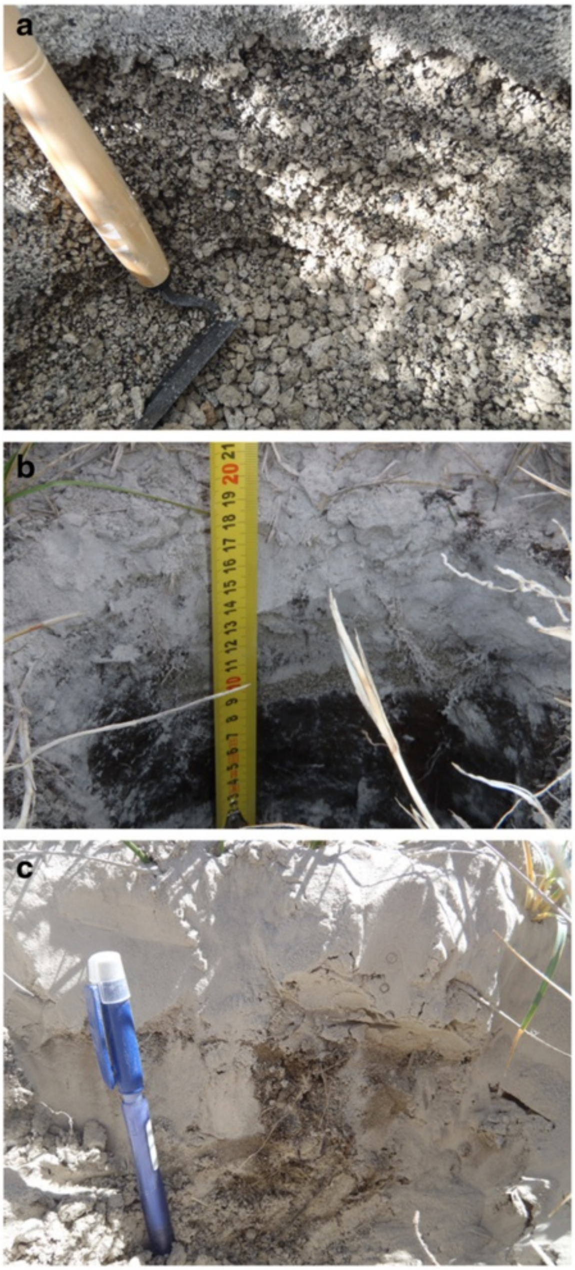

Fig. 2 Ash sample site photographs illustrating the difference in ash fall thicknesses and grain sizes along the deposit transect (see Fig. 1 for locations). **a** coarse ash near Villa la Angostura (53km from vent, 290mm thickness); **b** medium grained ash near Bariloche (100 km from vent, 30mm thickness); **c** fine ash in the steppe region near Jacobacci (240 km from vent, 40mm thickness)

Additionally, ashfall thickness thresholds, which can also be compared to CC-VC, have previously been placed on expected agricultural impacts by using a range of case studies (Wilson et al. 2009). These were developed based on field trials and numerous case studies. Initial attempts to place hazard intensity thresholds on clean-up actions are also applied to the three main towns affected by the CC-VC ashfall (Hayes et al. *in prep*). DDS were applied to the CC-VC impacted sectors regionally and based on the maximum damage that occurred due to the ashfall.

Although not assessed in detail in this study, there have been numerous previous attempts to try and match qualitative impact data with hazard intensity thresholds such as ashfall thickness (Table 2). Blong (Blong 2003a) began this work by recording impacts observed across numerous case studies and sectors and the associated hazard intensities. Whilst this did not result in true DDS, some crude thresholds were proposed (notably for agriculture), and recognition of the range of impacts that could occur due to ashfall led to increased recording of these indicators. Another approach was presented by Johnston (1997), where a vulnerability index was assigned to each geographic sector at various ashfall depths, based on the likelihood of a particular sector, a) 'becoming inoperable' and b) receiving 'damage.' This index was used to classify vulnerabilities for a specific geographic area in the North Island or New Zealand, and then used with various scenarios to predict impacts. This approach is useful as it considers the variations in infrastructure design and resilience across different areas, however it is reliant on specialist knowledge about the design and relative resilience of numerous sectors for each location. This scheme's main utility is in New Zealand-specific pre-EIA's and will not be applied in this study.

An earlier attempt at placing hazard intensity thresholds on agricultural losses also exists (Neild et al. 1998). The major focus is on vegetation loss of both pasture and horticulture, however the full range of agricultural impacts is not captured and only three broad grouping of impacts are used (Table 2). Despite these limitations, these previous studies formed the basis of the current DDS schemes that will be applied in this study.

Methods

In-field impact assessment

Impacts to infrastructure and pastoral systems were assessed during a three-week long impact assessment trip undertaken by the authors between 27 February and 16 March 2012; approximately nine months after the initial eruption sequence began. Semi-structured interviews were conducted with infrastructure managers, emergency managers, municipal officials and agricultural scientists in Villa la Angostura, Bariloche and Jacobacci. Five farmers were also interviewed. Interview sites were selected in an effort to gain data points along a transect of the tephra fall zones approximately parallel to the main tephra fall out axis where possible. This was to allow impacts at varying tephra thicknesses to be observed. Interviews were

Table 2 Review of previous damage/disruption states for agriculture and infrastructure systems after ashfall. Main classificiation systems used in this study in bold

Proposed in	Type	Sectors	Main case studies and data sources	Number of states	Hazard threshold type	Strengths	Weaknesses
Blong 2003b	Hazard intensity thresholds	All - notably agriculture (livestock health and horticultural crops)	Mt St Helens	5	Ashfall thickness	Qualitative statements about animal health, also done for horticultural crops not seen in the PCC-VC area	Information not placed within a specific damage state framework, does not acknowledge starvation, gastrointestinal blockages or feed supply issues
Neild et al. 1998	Hazard intensity thresholds	Agriculture (vegetation focus)	Mt St Helens, Ruapehu	3	Ashfall thickness	Part of a agriculture specific report, ideal for intended setting of New Zealand	Only 3 levels, so results within each are very generalised
Wilson et al. 2009	Hazard intensity thresholds	Agriculture (pastoral focus)	Ruapehu, Hudson, Chaiten	5	Ashfall thickness	Based on review of numerous case studies and authors own field work	Generalised descriptions based on relatively high-intensity farming systems
Wilson et al. 2014a	Damage and functionality states	Electrical, water, wastewater, transportation	Chaiten, Mt St Helens, PCC	4 (including 0)	Ashfall thickness	Supported by numerical relationships between thickness and functionality	Assume a relatively standard system of infrastructure design
Jenkins et al. 2014	Damage and disruption states	All	Various	6 (including 0)	Ashfall thickness	Includes all infrastructure sectors and agriculture, based on both prior case studies and expert elicitation	Descriptions are very generalised, and have not yet been widely applied
Hayes et al. 2015	Hazard intensity thresholds	Clean-up	Shinmoedake, Sakurajima, Mt St Helens	4	Ashfall accumulation	First comprehensive review of clean-up operations	Likely to differ dependent on a cities previous experiences with ashfall, and access to resources

conducted in Spanish through primarily native English speaking translators with experience living in South America and minuted. Questions were separated into those for urban infrastructure managers and rural production managers and farmers (Table 3). Follow up questions on technical or contextual points were used as required when more information was needed to accurately understand the nature and severity of the impacts. Interview methodology was reviewed and approved by the University of Canterbury (Christchurch, New Zealand) Human Ethics Committee prior to fieldwork.

Interview data was compiled and common themes identified. All expert judgement and observations referred to in the study are based on field interviews with affected stakeholders and farmers, investigations made during field work for this study, and findings recorded during interviews with agricultural agency staff, emergency management personnel, and other affected stakeholders. In order to quantify this observational impact data, damage states were assigned using performance-based indicators. This meant that primarily qualitative data collected through interviews could be placed in a more quantitative framework, allowing for more accurate comparisons to be drawn.

Table 3 General question schedule

Urban Interviews	Rural Interviews
(infrastructure managers, municipal managers and staff, researchers)	(farmers, agricultural agency staff, municipal production managers)
Amount and description of ash fall in area?	The same questions used for the urban interviews were used, with the addition of the following questions:
Wind/water remobilisation observed?	Farm size?
How did it affect your day-to-day life?	Annual production?
Were water supplies affected?	Animal numbers?
Building damage?	Changes in soil fertility?
Power supply disruption?	Any treatments for plants and to protect animals used?
Any communication issues?	Animal/crop losses sustained?
How was ash cleaned-up?	What supplementary food has been used?
Stabilization techniques?	How has the ash fall changed the way the area is farmed?
Ash dump locations?	What warnings were given before the ash fall?
Mitigation techniques employed?	Were any animals evacuated?
Any evacuations?	Details of animal movement
What emergency information was given by authorities?	
How was this communicated?	

Damage/disruption state application

Damage and disruption states were applied in two ways post-event. Firstly, they were applied to regional and municipal critical infrastructure and agricultural sectors using the observational and impact data collected in the field. Secondly, scales were applied to the impacted regions solely based on the ashfall thicknesses received. This approach relies upon the accuracy of published ashfall thickness measurements at each of the assessed sites (Fig. 1). Municipal and infrastructure staff reported thicknesses within the range of those published (Table 1). However, tephra thicknesses were consistently over estimated by farmers (Table 4), possibly due to misperception and localised over-thickening and dune formation (Wilson et al. 2012a). In these two approaches DDS were used both as a method of categorising post-EIA observations, and assessing how well average ashfall thicknesses predicted the CC-VC ashfall impacts.

Results

Agriculture

Pastoral farming style and production techniques vary widely within the depositional area of the ash fall, from small, dispersed operations in parklands of Parque Nacional Nahuel Huapi (Nahuel Huapi National Park), to extensive production on the arid steppe (Jacobacci and Comallo areas). Thus, the impacts of the ash fall, recovery paths and mitigation options are also variable. The main control on the different agricultural types and intensities is the temperate (Nahuel Huapi) and the semi-arid (Jacobacci/Comallo) zones (Fig. 3). Interviews took place at five main farm sites (Fig. 4; Table 4), with interviews with regional production managers and agricultural agencies also providing information.

Previous studies have identified the following issues for livestock arising from ash contamination of feed: starvation due to feed becoming unpalatable; gastrointestinal and rumen blockages following ash ingestion; and tooth abrasion (Cook et al. 1981; Cronin et al. 1998; Wilson et al. 2011b). These issues were also all observed to some degree in this study. However, the main cause of livestock losses across the impacted area was due to starvation and gastrointestinal blockages. Some livestock were also affected by skin and eye irritations and infections (Robles 2012), possible chronic fluorosis (Flueck & Smith-Flueck 2013; Flueck 2014; Flueck 2013), and in Jacobacci there was a decline in wool quality and shearing rates (Aguirre 2012; Easdale et al. 2014; Wilson et al. 2012b).

Maintaining clean feed supplies was considerably more challenging in the steppe region where severe wind remobilisation of the ashfall deposit began immediately and persisted for over 12 months. Drought conditions prior to the ashfall also contributed to the increase in

Table 4 Impacts on agricture at study sites (NHNP[a] indicates Nahuel Huapi National Park land)

	Farm characteristics				Ash Thickness (mm)		Animal Numbers (Losses in brackets)		
Farm ID	Location	Farm Size (ha)	Approximate rainfall (mm/year)	Animal water source	Farmer Est.	Wilson et al. 2012c	Cows	Sheep	Goat
A	Rio Totoral	NHNP	800	Stream/lake	600	300+	~50 (~46)	-	-
B	Eastern side of Lago Nahuel Huapi	NHNP	800	Stream/lake	500	300+	~50	-	-
C	Comallo Valley	1000	120	Troughs from underground wells	70	50	50	164 (121)	-
D	Outskirts of Comallo Township	10	120	Troughs from underground wells	30–40	30–45	-	20–30 (5)	-
E	Eastern end of the Comallo Valley	40	120	Troughs from underground wells	20	50	200 (35)	1600 (400)	-

	Animal Symptoms							Vegetation Issues	
Farm ID	Eye and skin irritation	Immobilisation	Tooth abrasion	Starvation/ dehydration	Gastro-intestinal blockages	Fluorosis	Loss Causes	Vegetation losses (%)	Vegetation loss cause
A	✓	-	✓	-	✓	✓ (chronic)	Starvation and lack of clean water.	25	Burial
B	✓ (on-going)	-	✓	-	✓	✓ (chronic)	Evacuated animals as soon as possible. Killed some for household use.	25	Burial and remobilisation
C	✓ (on-going)	-	✓	✓	✓	✓ (chronic)	Starvation (no spring grass), dehydration (stream dried up) and rumen blockages. Tooth abrasion. 6-year drought compounded problems.	50	Burial and remobilisation
D	✓ (on-going)	-	✓	✓	✓	✓ (chronic)	No autopsies. Remobilisation issues. Also experienced losses from 1960 PCCVC ashfall due to stomach blockages	25	Burial and remobilisation
E	✓ (on-going)	-	✓	✓	✓	✓ (chronic)	Ash in rumen causing stomach blockages. Tooth abrasion. Issues with water supply.	25	Burial and remobilisation

[a] Farmers in the Nahuel Huapi National Park (NHNP) are assigned parcels of land based on animal numbers and the number of animals already in the immediate area. Land boundaries are not strictly adhered to and animals freely graze the park

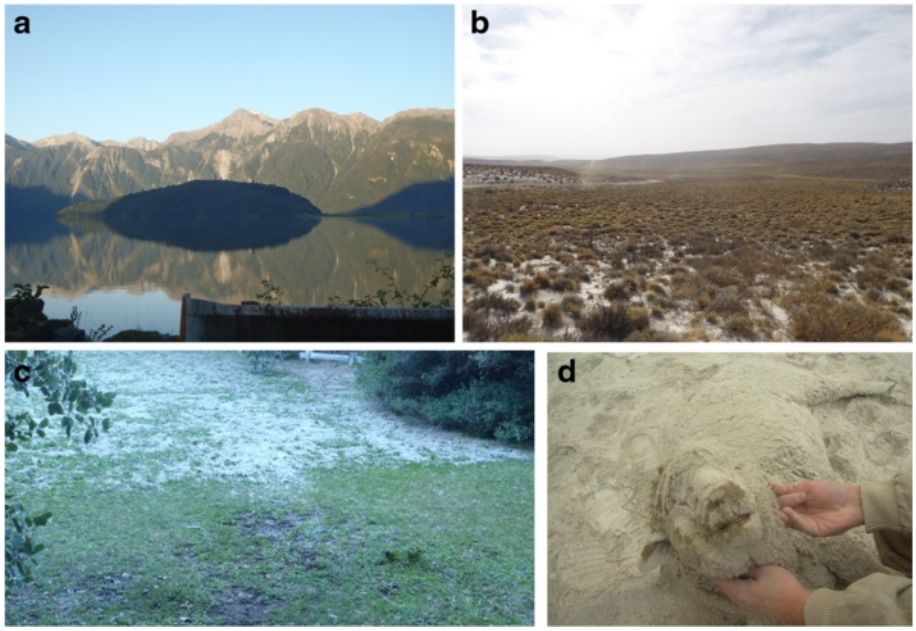

Fig. 3 **a** temperate region of Lago Nahuel Huapi and Nahuel Huapi National park; **b** agricultural area near Jacobacci on the semi-arid steppe; **c** ash-covered clearing used by grazing animals within the Nahuel Huapi National Park, nine months after initial eruption; **d** ash covered sheep that farmer believed died of starvation near Jacobacci (Photo credit: José Mellado)

losses sustained in the steppe region (>40%) compared to the temperate, Nahuel Huapi National Park area. Drought on the steppe left pasture and livestock in poor condition, feed supplies depleted, and farm systems vulnerable. In contrast, losses in the national park area were more manageable as they were similar to those sustained after a severe winter (~25%; Table 4). This was due to higher rainfall rates rinsing feed and aiding the integration of ash into soil through increased weathering and soil renewal rates, better animal condition leading into the event, and more livestock evacuations taking place. This grouping of agricultural losses by climatic zones is useful to also explain what was observed after the 1991 Hudson eruption, where despite receiving lower levels of ashfall, production losses on the semi-arid steppe were higher than expected due to continued wind remobilisation of ash deposits (Wilson et al. 2011b).

When assessing agricultural losses due to the 2011 CC-VC ashfall using DDS (Jenkins et al. 2014) and impact thresholds (Wilson et al. 2009), the national park region performed much better than expected given the large thicknesses received (>300 mm). This is demonstrated by both current schemes (Fig. 5a & b) and the two older scales (Neild et al. 1998 & Blong 2003b; Fig. 5c & d), as based on thicknesses damage should have been much more severe, with decades of recovery and retiring of land predicted (Tables 5 and 6; Fig. 5). The more positive outcome may be due to the unique style of farming in the area, where animals are free to roam large distances of parkland at low stocking rates and are used to foraging for food where possible. Vegetation recovery was also more rapid compared to recovery in the semi-arid area, with to the high levels of rainfall and the temperate climate being favourable to ash weathering and incorporation into the soil (Shoji et al. 1993). The performance of both livestock and vegetation means that the existing DDS and hazard intensity thresholds do not correspond well with the scenario faced in the national park region.

In contrast, the scales correlate well with the agricultural impacts and hazard intensities faced in the steppe region (Tables 5 and 6; Fig. 5). This is unexpected due to the extreme climatic conditions faced. Farming conditions prior to the eruption were already marginal, with farmers often having to purchase supplementary feed due to drought conditions. The area also faced an extreme amount of wind remobilisation, where months after the ashfall event animals still needed to be sheltered during windy conditions. These conditions are not typical of what would occur after ashfall events in other volcanically active countries with more productive agricultural settings (e.g., New Zealand, Japan, Indonesia, etc.). Therefore as DDS scales correlate well with losses in the steppe it is unlikely that the scales would be good indicators of impacts in more agriculturally favourable conditions.

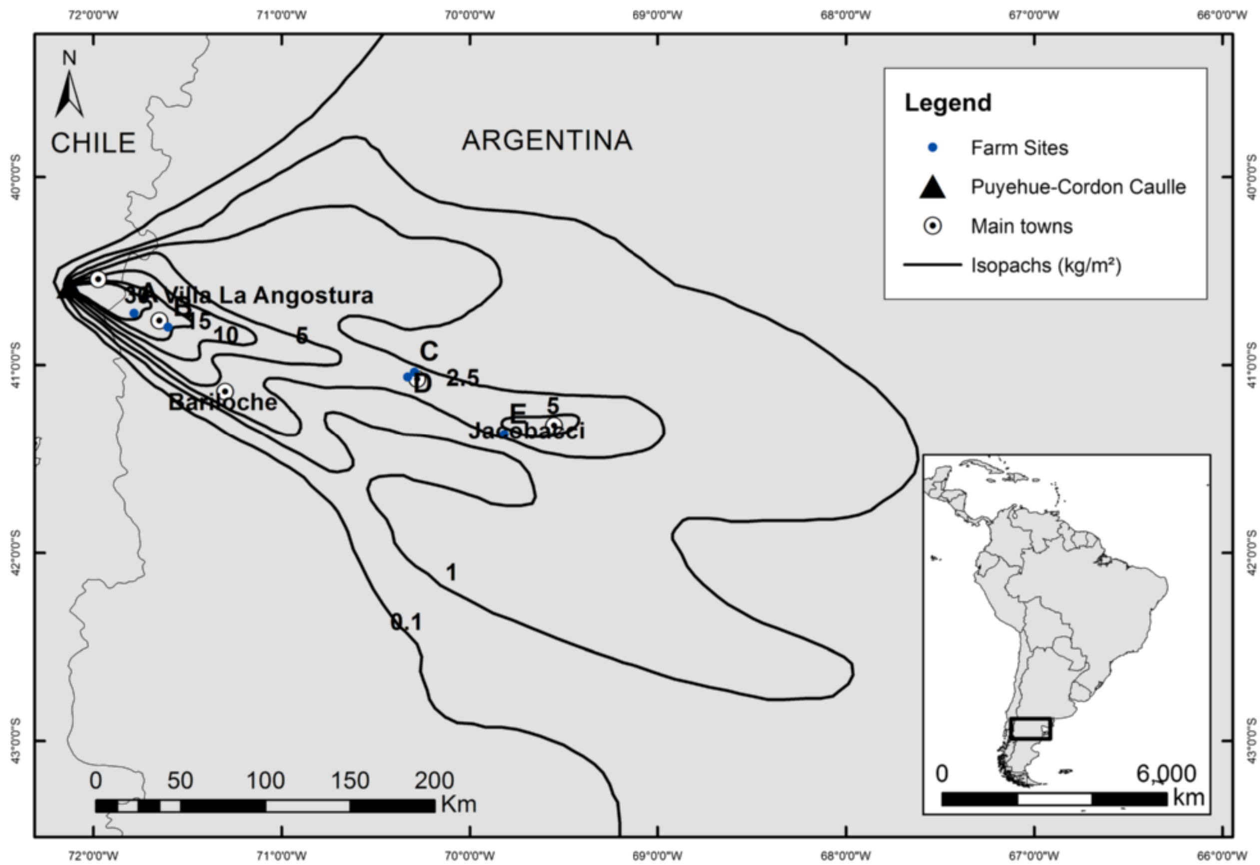

Fig. 4 Map of farm sites (**a**-**e**) where in-depth farmer interviews were undertaken (Table 4)

Critical infrastructure

Electrical systems

The ashfall caused widespread disruption of electricity supplies in the study area. As observed for other eruptions with similar urban ashfall thicknesses (Tables 7 and 8), the effect of ash contamination on electrical distribution lines and substation insulators was induced leakage currents and insulator flashover, and the blockage of air intakes at thermal oil and coal fired generation plants (Wardman et al. 2012). In addition, continual tripping of switches due to flashover events, combined with the presence of fine ash in switches, led to abrasion of the metallic conductors that reduced the contact between electrodes, reducing their functionality. This required ongoing replacement of the switches, particularly in the Jacobacci area (Fig. 6; Table 9). Thermal generation facilities also suffered significant disruption in both Bariloche and Villa La Angostura, mainly due to ash blockage of air intakes (Table 9).

The most commonly employed mitigation measure across the three main centres was to spray insulators and lines with high-pressure hoses. This was effective in the short term but further ashfalls or wind remobilisation would require repeated cleaning. Increasing the length of insulator pins in Villa la Angostura was trialed and proven to be effective at preventing ashfall-induced flashover. This resulted in all pins in the town eventually being upgraded, which has increased the network's resilience to future events (Table 10). Management of the power cuts in Bariloche included the development of a 20 MW diesel generation plant (Fig. 6 b; Table 10), however this did not cover the full 45–55 MW requirements. Consequently, Bariloche continued to experience problems with air intakes becoming clogged with ash (Table 9). DDS were assigned to the electricity network impacts for Villa la Angostura, Bariloche, and Jacobacci. The disruption experienced in Villa la Angostura was less severe than predicted by DDS, and there were no components seriously damaged or line breakages in Bariloche as the Wilson et al. 2014a DDS suggest may occur (Table 11; Fig. 7). DDS descriptions assigned based on ash thicknesses were accurate for Jacobacci, despite the fact that most damage occurred due to wind remobilisation abrading components. Severe wind remobilisation, such as that which occurred on the semi-arid steppe, is not usually experienced in temperate environments, which again could possibly suggest that the DDS

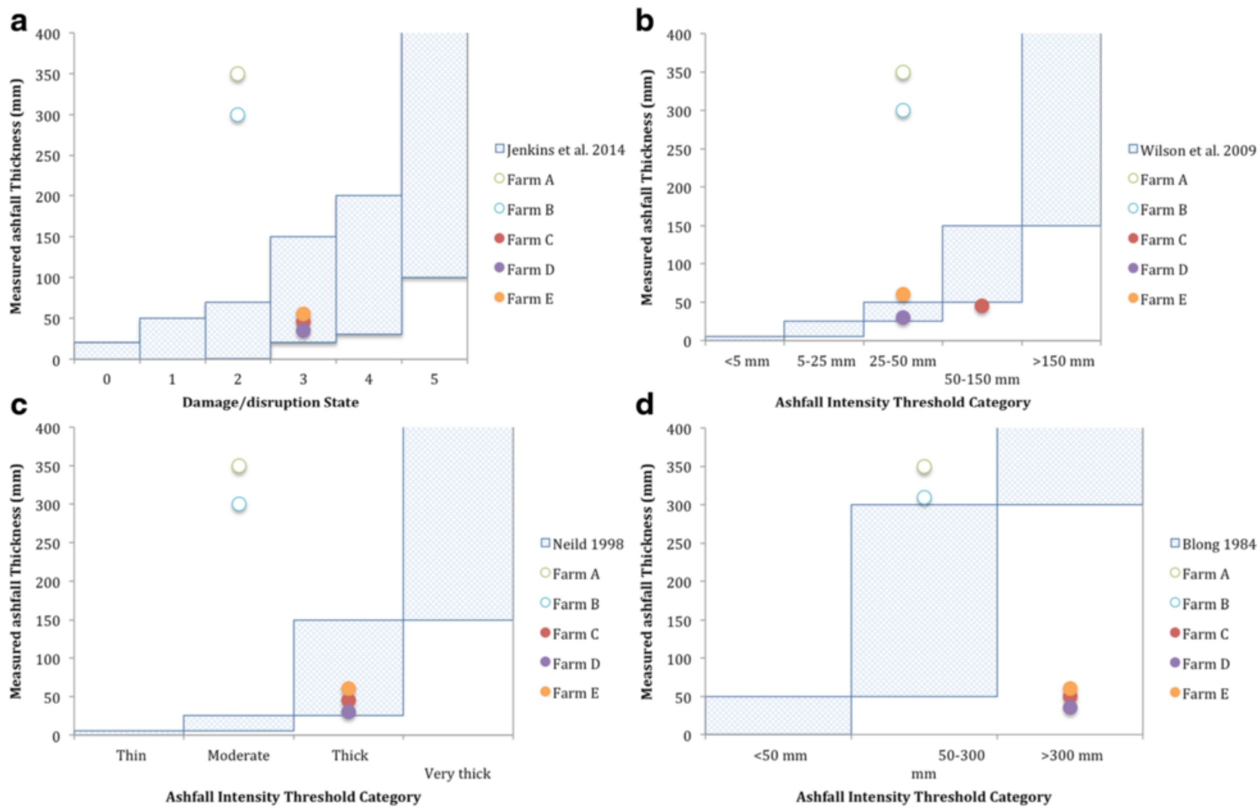

Fig. 5 Graphs showing the thicknesses of tephra received compared to the damage/disruption states that the farms were within based on descriptions, for four different schemes (**a**) Jenkins et al. 2014; **b** Wilson et al. 2009; **c** Neild et al. 1998; **d** Blong 2003a). Hollow points show farms where extensive, prolonged wind remobilisation did not occur

hazard thresholds would not work in all climatic scenarios.

Water supply

Villa la angostura In Villa la Angostura, the town centre is supplied with water by a relatively advanced treatment system. From dual intakes on Lago Correntoso and Lago Nahuel Huapi, water is pumped 80 m uphill to a treatment plant where there is an initial filtration step followed by pressure sand filtration then chlorination (Fig. 8). The eruption increased the level of ash suspended in the lakes, which caused high levels of wear and tear on pumping equipment. For instance, one pump had been in service since 1997 with no problems, but had to be completely replaced after the eruption. Power outages also caused problems for this system, which relies on pumping, and generators were brought in to maintain pumping.

Outlying neighbourhoods are served by a range of smaller and more rudimentary systems with intakes either in the lakes or in streams, followed by initial passage through flow control/settling basins then treatment via slow sand filter beds followed by chlorine dosing. These systems are in general poorly maintained, with inadequate removal of suspended solids and organic debris compromising disinfection. Tap water sampling carried out on 11 July 2011 by the municipal laboratory reported inadequate residual chlorine (<0.2 mg/L) to prevent reinfection in the distribution system (data courtesy of A. Murcia, Bromatología Municipalidad de Villa la Angostura, reported in Wilson et al., 2012b). Stream-fed systems were severely affected by the eruption; with intake structures inundated with ash, requiring manual cleaning. These systems continued to experience problems in rainy conditions when remobilised ash was deposited in the catchment. To meet demand at the time, water was distributed by the Army to affected neighbourhoods in 1000-litre tanks, along with pallets of bottled drinking water. To meet continuing demand, a new 21-m deep well was excavated.

Bariloche The Bariloche water treatment plant (WTP) provides around 80% of the city's water supply, with outlying neighbourhoods supplied by a range of smaller systems with intakes from springs, streams and Lago Nahuel Huapi (Table 9). Effects of the eruption on these smaller systems were similar to those described for Villa la Angostura and are not described again here.

Table 5 Comparison of PCC-VC ashfall impacts to interviewed farms with existing damage state scales

Farm ID	Ash thick-ness (mm)	Damage State based on thickness (Wilson et al. 2009)[a]	Damage state description	Damage state based on observations	Justification of assigned damage state	Damage state based on thickness (Jenkins et al. 2014)	Damage state description	Damage state based on observations	Justification of assigned damage state
A	300+	>150mm category	New soil formation needs to occur (up to decades)	25–150 category	Ash was incorporated into soil within months	5	Major rehabilitation required/retirement of land	2	No land was retired and very little rehabilitation work was undertaken
B	300+	>150mm category	New soil formation needs to occur (up to decades)	25–150 category	Ash was incorporated into soil within months	5	Major rehabilitation required/retirement of land	2	No land was retired and very little rehabilitation work was undertaken
C	50	25–150 category	Integration of tephra into soil in 1–5 years	50–150 mm category	Recovery will be limited within the next growing season	2–3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place
D	30–45	25–150 category	Integration of tephra into soil in 1–5 years	25–150 category	Forecast time to total recovery (~5 years) is within what is predicted for the area	2–3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place
E	50	25–150 category	Integration of tephra into soil in 1–5 years	25–150 category	Forecast time to total recovery (~5 years) is within predictions	2–3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place

[a] Not suggested as true damage states, rather guidelines for what impacts to expect

The centralised WTP has an intake in Lago Nahuel Huapi with electrical pumping of water up a 150 m rise to storage tanks. As the turbidity in the lake is almost always very low (0.2–0.4 NTU), the treatment train does not include an initial coagulation/flocculation step prior to filtration. Following the eruption, turbidity in the lake increased to an unprecedented 26 NTU. Suspended ash entered the treatment system through the intake pipes and via direct fallout, and caused a range of problems. Pumps suffered accelerated wear and tear, with impellers suffering three years' wear in six months. Ash also entered the drive shaft assembly above a pump motor, and caused it to become unbalanced and exposed to additional load. Ash also contaminated the open-air sand filter beds (Fig. 9). In general, all these problems were manageable, but a greatly increased level of maintenance was required. The only interruption to production was when a city-wide power outage of 12 h duration occurred, and for the first time in twenty years, no water was supplied to central Bariloche.

Jacobacci In Jacobacci, the town's water supply is based on extraction from a system of 17 groundwater wells. Wellhead pumps are enclosed in pump houses. The water is chlorinated then distributed to households. As the system is completely enclosed, it proved to be resilient to ash (Tables 9 and 10). The main challenge was meeting water demand. Due to continued wind remobilisation and ash redeposition, water demand would increase as the community cleaned up and dampened

Table 6 Comparison of PCC-VC ashfall impacts to agricultural areas with existing damage state scales

Affected area	Ash thick-ness (mm)	Damage State based on thickness (Wilson et al. 2009)[a]	Damage state description	Damage state based on observations	Justification of assigned damage state	Damage state based on thickness (Jenkins et al. 2014)	Damage state description	Damage state based on observations	Justification of assigned damage state
Nahuel Huapi National Park	250–400	>150mm category	New soil formation needs to occur (up to decades)	25–150 category	Whilst ash did need to be incorporated into soil this occurred over months rather than years/decades	5	Major rehabilitation required/ retirement of land	2	No land was retired and very little rehabilitation work was undertaken (due in part to it being a national park)
Steppe Region (incl. Jacobacci)	40–60	25–150 category	Up to 5 years recovery time	25–150 category	~	2–3	Minor to major productivity loss (remediation required)	3	Losses were >50% across the region, however due to lack of resources very little remediation took place

[a] Not suggested as true damage states, rather guidelines for what impacts to expect

down ash in the streets, from normal usage of 1 million L/day to as high as 3 million L/day.

Role of system design The critical importance of system design in determining resilience to ashfall impacts is illustrated by comparing impacts on water supply systems in Bariloche (which received 30–45 mm ashfall) and Jacobacci, which received 50 mm ashfall initially and was also subjected to prolonged exposure to wind-remobilised ashfall from upwind deposits (Tables 7 and 8). At Jacobacci, the water supply system is based entirely on groundwater extraction, and as all parts of the system are enclosed, the system proved resilient to the ashfall. However, the town did experience a sustained period of increased water demand after the eruption, which necessitated the excavation of a new well. In contrast, the city of Bariloche received a similar initial ashfall. A water treatment plant that has a surface water intake and also has open-air sand filter beds supplies the central city. While the plant was able to maintain production (apart from an interruption caused by a 12-h long power outage), a greatly increased level of maintenance of pumping equipment and the sand filter beds was required to manage problems caused by the presence of ash in the treatment system.

Water supply systems were not included within the Jenkins et al. (2014) scheme due to difficulties in relating impacts to a single hazard intensity measure such as thickness. This highlights the difficulty in creating a standardised scale for water systems. The varied nature of multiple interconnected systems or many independent systems within the same catchment, both within a single urban area and when comparing between different towns, means that the creation of damage states for water systems is highly problematic. Jenkins et al. 2014, argues that these difficulties are insurmountable with current impact information, however Wilson et al. 2014a has attempted to create a scheme. The Wilson et al. 2014a damage states were applied to water supply systems for the three main urban centres; here we apply them only to the central water treatment plant in each of the towns, rather than the smaller peripheral treatment sites. This is due to the lack of detailed information at all of the smaller sites, and that the Wilson et al. 2014a scheme is better suited to larger centralised treatment plants.

Water supply systems in Villa la Angostura and Jacobacci both performed better than predicted, based on the application of the Wilson et al. 2014a DDS (Table 11; Fig. 10). In Villa la Angostura there were no reports of roof collapse over treatment sheds, and whilst water demand was raised the supply was not exhausted, unlike what is suggested by the Wilson et al. 2014a DDS. This is likely due to the variety of water sources available preventing supplies being exhausted, that clean drinking water was trucked in, and possibly that the steep pitch of roofs (designed for yearly snowfalls) reduced adherence of ashfall to roofs resulting in a decrease in the cleaning required. The DDS system applied was not designed to take into account the resilience of the Jacobacci completely covered supply system (Table 11; Fig. 10). This meant that there was no damage to equipment or tanks, and no issues with contamination of municipal supplies.

Waste water systems

A centralised wastewater collection and treatment system serves the urban population of Bariloche (Table 9; Fig. 11). During the eruption, an estimated 1.5 million cubic metres of ash was deposited on the city of Bariloche. While the sewer lines and storm water drains for the city

Table 7 Ash thicknesses with impacts compared to previous ashfall events 2010-2012 (NI - Not investigated within studies; NA- Not applicable)

Eruption		PCC-VC 2011					Tongariro 2012	Shinmoedake 2011		Sakurajima 2011	Tungurahura 2010
Localities impacted		Villa la Angostura		Bariloche		Jacobacci	Rangipo	Kirishima	Miike	Kagoshima	Riobamba
Ash thicknesses (mm)		150–170		30–45		50	2	1	60–80	1	10
Electricity	Flashover	✓		✓		✓	✓				
	Air intakes clogging	✓		✓							
	Switch abrasion										
	Controlled outage								✓		✓
	Generator blockage					✓					
		Stream-fed	Main WTP	Stream-fed	Main WTP						
Water	Turbidity increase	✓	✓	✓	✓		✓	NI	NI	NI	
	Damage to pumps		✓	✓	✓			NI	NI	NI	
	Filtration contamination	✓			✓			NI	NI	NI	
	Clogging of filters	✓	✓	✓				NI	NI	NI	
	Increased demand	✓	✓	✓	✓	✓		NI	NI	NI	
Waste water	Effects on sewer networks (clogging, wear on pumps)	NA		✓		NA	NI	NI	NI	NI	NI
	Damage to pre-screening equipment	NA		✓		NA	NI	NI	NI	NI	NI
	Power outages affecting pumping	NA		✓		NA	NI	NI	NI	NI	NI
	Ash accumulation in treatment tanks	NA		✓		NA	NI	NI	NI	NI	NI
Roading	Road closures	✓		✓		✓	✓		✓		
	Air filter blockage	✓				✓					
	Decreased traction	✓		✓		✓					
	Decreased visibility	✓				✓		✓			
	Road markings covered	✓		✓		NA	✓	✓		✓	
Airport	Airport closed	NA		✓		NA	NA	NA	NA	✓	✓

are theoretically separate, there are in fact many illegal connections, and thus ash entered both the stormwater and sewer networks despite barriers and sandbags being put in place in an attempt to exclude it. A further impact on the sewer network occurred on the 6/7 June 2011, when the city was affected by a widespread power outage related to the ashfall. Not all pumping stations had emergency generators, although most had sufficient storage capacity to allow for six to eight hours of accumulation before overflows of raw sewage occur (Table 9). The situation was managed by manually moving emergency generators around between pumping stations (Table 10).

At the treatment plant, ash accumulated in the biological reactor. This reactor is open-air; however most ash entered the tank through the intake rather than from direct fallout. The reactor is 4.5 m deep, and the plant operator estimated that approximately 1 m of ash had accumulated in the bottom. This did not interfere with the functioning of the microbial population in the pond, but did reduce the plant's capacity. The ash caused few problems for the initial screening of wastewater (manual screening through static bars, followed by pumping up to a decanter for primary sedimentation.

No DDS were created for waste water in the Jenkins et al. (2014) study, as the complexity of waste water systems and their interaction with hazard characteristics is not easily quantified. Similar to the issues faced for water supplies, a range of hazard and vulnerability characteristics led to the Jenkins et al. (2014) study deciding to exclude waste water systems. However, using the DDS and hazard thresholds available (Wilson et al. 2014a), the Bariloche plant appeared to perform as expected given the ashfall thickness received (Table 11) with temporary disruptions to waste water services, pump abrasion, and sedimentation in treatment plants being the main impacts (see Table 9 for full list of impacts).

Table 8 Ash thicknesses with impacts compared to previous ashfall events 1980-2010 (NI - Not investigated within studies; NA- Not applicable)

Eruption		Pacaya 2010	Chaiten 2008		Ruapehu 1995/96	Rabaul 1994	Mt Spurr 1992	Hudson 1991		Mt St Helens 1980
Localities impacted		Guatemala City	Futaleufu	Esquel	Gisborne	Rabaul	Anchorage	Perito Moreno	Los Antiguos	Yakima
Ash thicknesses (mm)		20–30	80	15	3	600–1000	3–5	30–40	75	6–10
Electricity	Flashover	✓	✓	✓	✓	NI	NI			✓
	Air intakes clogging					NI	NI			
	Switch abrasion					NI	NI			
	Controlled outage	✓				NI	NI			
	Generator blockage		✓			NI	NI			
Water	Turbidity increase	✓	✓	✓	✓	NI	✓	✓	✓	✓
	Damage to pumps	✓		✓		NI		✓		
	Filtration contamination					NI	✓			
	Clogging of filters		✓			NI	✓		✓	
	Increased demand		✓	✓		NI				✓
Waste water	Effects on sewer networks (clogging, wear on pumps)	✓				NI	✓	NI	NI	✓
	Damage to pre-screening equipment	✓				NI		NI	NI	✓
	Power outages affecting pumping	✓				NI		NI	NI	✓
	Ash accumulation in treatment tanks	✓				NI		NI	NI	✓
Roading	Road closures		✓	✓	✓	✓		✓	✓	✓
	Air filter blockage		✓	✓						
	Decreased traction		✓	✓	✓	✓		✓	✓	✓
	Decreased visibility		✓	✓	✓	✓	✓	✓	✓	✓
	Road markings covered		✓	✓		✓				✓
Airport	Airport closed	✓	NA	NI	✓	✓	✓	NA	NA	✓

Roading

Route 40 (the main road into Patagonia), Route 231 (between Villa la Angostura and Bariloche) and Route 23 (connecting Bariloche and Jacobacci) all experienced periodic road closures and speed restrictions related to the lack of visibility and issues with vehicular traction on the roads (Table 9). In the temperate zone the major issue facing road users was the thickness of ash on the road. This meant that vehicles were unable to gain traction, and even four-wheel drive vehicles were sometimes unable to use the roads when thicknesses exceeded 100 mm. The volume of ash and issues with the clogging of air filters also meant that clean up vehicles struggled to gain access to some areas for clean-up. This was overcome by compaction of the deposit and gradual clean-up. The border crossing between Chile and Argentina at the Samore Pass was closed for several weeks as the ash fall thickness reached over 300mm.

In Jacobacci and the surrounding steppe region, the lack of visibility meant that no urban clean up of roading started for the first week, slowing the reopening of the town's major roads. Driving conditions in the steppe area remained treacherous for many months after the initial eruption, especially in areas where the ashfall was thicker than 100 mm (Fig. 12a & b). Due to remobilisation in the area, visibility issues persisted in the steppe region and air filters became clogged with ash and needed cleaning and replacing regularly (Fig. 12c; Table 10). Dampening down ash and restricting vehicle speeds was employed to try and allow traffic on the roads to continue to be used (Fig. 12d; Table 10). Despite these measures driving remained a challenge on windy days due to low visibility even up to 18 months after the eruption.

Roading networks impacted by the CC-VC ashfall performed similarly to other eruptions in the region with comparable tephra thicknesses, such as the 1991 Hudson eruption (Wilson et al. 2012c), and the 2008 Chaitén eruption (T.M. Wilson, *unpublished field notes*). Many other eruptions that experienced much lower ash

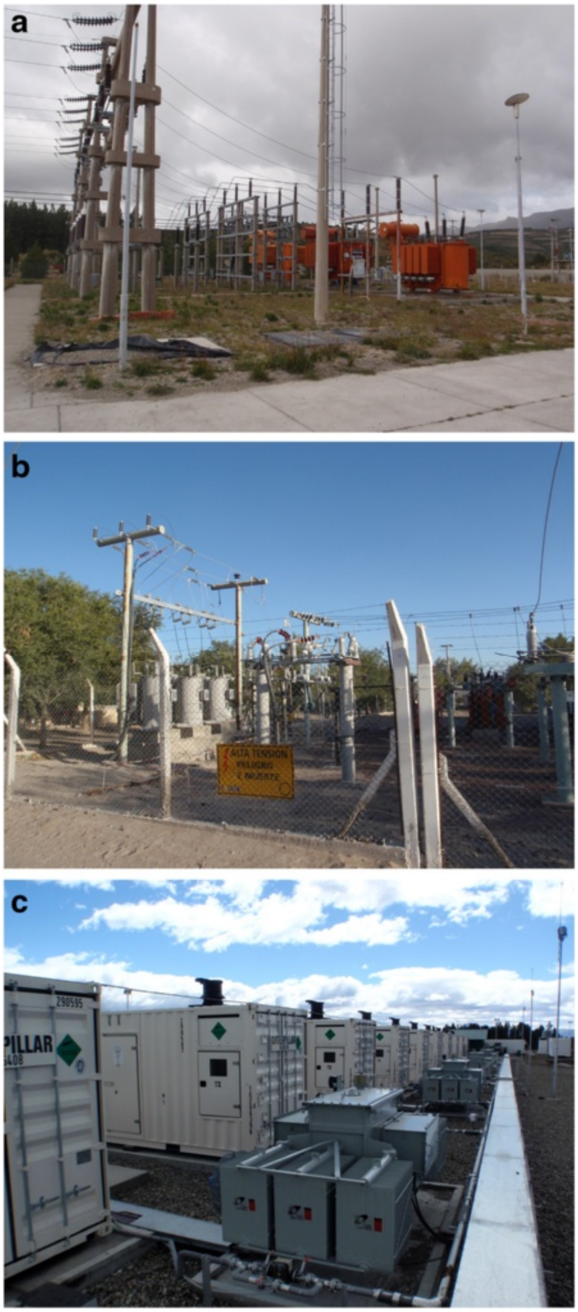

Fig. 6 a Outdoor grid exit point substation for Bariloche; **b** 20 MW diesel generation plant installed to help with power cuts after the ashfall; **c** Grid exit point substation near Jacobacci

thicknesses still experienced similar issues with roading networks, demonstrating the low overall resilience of roading to ashfall (Tables 7 and 8).

Roading in Villa la Angostura (under the G. Wilson et al. (2014) scale) and Bariloche (under the Jenkins et al. (2014) scheme) was able to function better than the thick ashfall deposits and previous experiences would suggest (Table 11; Fig. 13). A possible reason for this is that people in the area may have experienced ashfall before (1961 CC-VC, 1991 Hudson, and 2008 Chaitén eruptions) and therefore have a higher tolerance for the conditions and are more likely to drive. Conversely, DDS predicted lower disruption than what occurred in the Jacobacci steppe region (Table 11; Fig. 13). This is expected, as the severity and duration of wind remobilisation in the area is much greater than what would be experienced in a temperate region (Wilson et al. 2014a; Table 10, Fig. 12), with wind remobilisation continuing to impact public health and visibility in towns, farming areas and road networks for at least 18 months after the initial ashfall event. One DDS scale also suggested the possibility of structural damage to some bridge structures due to ashfall loading, this was not observed after the CC-VC event even on the Samore Pass, which received ashfall depths of up to 500 mm far exceeding the upper limit placed on the highest DDS (>150 mm; Wilson et al. 2014a).

Airport

The closure of Bariloche airport caused major disruption to the tourism industry in the region. The airport closed on the 4 June 2011 and did not reopen for 31 days, causing economic impacts for a region that relies heavily on both domestic and international tourism (Table 9; Fig. 14). Airport managers cleaned over 1,000 tonnes of ash from the runway and surrounding facilities during this time (Table 10). Following the clean-up the ash was deposited in depressions in the surrounding land and revegetated, with the installation of a comprehensive irrigation system accelerating vegetation growth as well as preventing remobilisation and redeposition of the material back onto the runway.

Even though the airport re-opened for business on 5 July, it was many more months before the country's two major airlines (LAN Chile and Aerolineas Argentinas) resumed regular services to Bariloche, as eruptive activity continued at Cordón Caulle. The decision to fly rests with individual airlines, with standard procedure to avoid flying through any ash plume. From the perspective of pilots, the problem was that they did not have a good system for identifying small, diffuse plumes. A further complication was that the ash forecasting model developed by the National Meteorological Service, and posted on their website for airlines to use, was perceived by airlines as being too 'experimental'. The acknowledgement of uncertainties associated with the data and modelling deterred airlines from its use. As there were no defined safe parameters for ash plume density, there was uncertainty about whether insurance companies would continue to provide coverage. This meant that the

Table 9 Summary of system design and impacts for infrastructure after the 2011 PCC-VC eruption

Infrastructure	Towns	Design	Impacts	Main issues
Electricity	Villa la Angostura	Not connected to national grid; 6.1MW thermal generation plant	Flashover on 13.2 kV, 380 V, and 220 V networks due to damp ashfall; Dry ashfall clogged air intakes for the thermal plant resulting in precautionary shutdowns	Flashover; air intake clogging
	Bariloche	Single transmission line and one grid exit point from national grid; Outdoor GXP substation	Whole town lost power for 8 h, with some not reinstated for 24 h after the initial ashfall; power cuts due to GXP substation suffering flashover due to ash; contamination of switches and busbars; diesel and gas generators were deployed around the town but the air intakes became blocked with ash	Flashover; air intake clogging; switch abrasion; generator blockage
	Jacobacci	Single transmission line and one grid exit point from national grid; Outdoor GXP substation	Some flashover caused intermittent power cuts to the town (usually for only a few hours); Tripping of switches due to flashover and abrasion of metallic components	Flashover; switch abrasion
Water Supply	Villa la Angostura central system	Town centre supplied by Lomas del Correntoso treatment system. Water is extracted from Lago Correntoso and Lago Nahuel Huapi then pumped up an 80 m rise to the WTP. An initial filtration step is followed by pressure sand filtration then chlorindation then gravity fed to households.	The eruption increased the level of suspended ash in the lake, which caused high levels of wear and tear on pumping equipment. Power outages also caused problems for this system.	Turbidity increase; damage to pumping equipment
	Villa la Angostura peripheral systems	A range of smaller systems based on intakes from streams or the lake. Systems are generally gravity-fed. System designs vary considerably, but in general the stream-fed systems are poorly maintained and do not achieve a good level of sediment removal prior to chlorine dosing. Water supplied to households may not contain adequate chlorine residuals.	Stream-fed systems were severely affected by the eruption, with intake structures inundated with ash. These systems continued to experience problems in rainy conditions when further ash was washed downstream. Some systems have been abandoned.	Damage to intake structures; turbidity increase; other contamination of raw water source; clogging of filters; overall system failure
	Bariloche central system	Bariloche's central water treatment plant has an intake in Lago Nahuel Huapi. Water is pumped up a 150 rise to storage tanks. The treatment process does not include a preliminary coagulation/flocculation step as intake water is normally very low in turbidity (0.2–0.4 NTU). Filtration is through open-air slow sand filters prior to chlorination.	The eruption increased the level of suspended ash in the lake, which not only caused accelerated wear and tear on pumping equipment but also allowed ash to enter the treatment plant (both via the intake and by direct fallout) where it clogged open sand filter beds. A greatly increased level of maintenance was required to manage these problems and remain in production. A city-wide power outage caused an interruption to water production.	Turbidity increase; damage to pumping equipment; clogging of filters
	Bariloche peripheral systems	Similar to range of smaller systems in Villa la Angostura; outlying neighbourhoods supplied by smaller systems with intakes from springs, streams and the lake, with wide variety of treatment system design.	Effects were similar to, though less severe than, for Villa la Angostura.	Damage to intake structures; turbidity increase; clogging of filters
	Jacobacci	17 groundwater wells with well-head pumps enclosed in pumphouses; water then chlorinated and distributed	This system is completely enclosed and thus proved resilient to the ashfall. However problems were experienced with high water demand as the town was repeatedly subjected to wind-remobilised ash and additional water was required for clean up	A sustained increased water demand

Table 9 Summary of system design and impacts for infrastructure after the 2011 PCC-VC eruption *(Continued)*

Waste water	Villa la Angostura	Not investigated during field visit		-
	Bariloche	Treatment plant 4.3 km east of the city; pumped to plant then screened through 25 mm bars, pumped through a decanter, then through a anaerobic tank before entering the biological reactor (*Nocardia spp*. Bacteria), finally wastewater sludge is separated and taken to the dewatering plant	Solids coming into the plant increased from 4500 mg/L to 8000 mg/L in the 3 days after the eruption due to ash contamination; sewer lines and storm drains were meant to be separated but sometimes illegally connected which meant large volumes of ash entered the system; power cuts meant that pumping stations without generators stopped; pump impellers had accelerated wear; 1 m of ash accumulated in the bottom of the 4.5 m deep biological reactor which reduced the plants capacity	Blockages of stormwater catchpits and sewer lines and junctions; accelerated wear and tear to sewage pump impellers; power outages affected pumping
	Jacobacci	Not investigated during field visit		-
Roading	Villa la Angostura	Asphalt main roads, unsealed secondary routes	Route 231 (asphalt) connecting Villa la Angostura with Bariloche was closed after the eruption for a day, then reopened but with speed restrictions; the Samore Pass border between Chile and Argentina was closed for several weeks after the eruption due to the thickness of ash recieved (>300 mm); drivers reported a loss of traction, inability to see road markings, and some issues with air filters becoming clogged	Road closures; road markings not visable; loss of traction; air filter clogging
	Bariloche	Asphalt	Route 40 (asphalt) the main road into Patagonia was closed for two days after the eruption; main road within the town were covered with 50 mm of ash therefore authorities recommended that cars stayed off the road	Road closures; road markings not visable; loss of traction; air filter clogging
	Jacobacci	Predominantly unsealed	Visibility an issue due to wind remobilisation, this prevented almost all driving and clean up for the first week; road between Jacobacci and Bariloche closed for a few days, then reopened to limited traffic at low speeds	Road closures; low visibility; road markings not visable; loss of traction; air filter clogging
Airports	Bariloche	Fourth largest airport in Argentina; located 13 km outside of Bariloche; airport land covers 1,810 Ha with a 2,400 m runway	Airport was closed for a month due to ashfall; approximately 1000 tonnes of ash was deposited onto airport land; when the airport reopened some airlines (LAN Chile and Aerolinas Argentina) did not recommence flights due to fears around ashfall and accurate forecasting; full service resumed on 20 December 2011	Airport closure; airlines reluctant to resume flights

closure at Bariloche airport was longer and therefore more damaging to the local economy (Table 10).

Due to the low tolerance of airports to ashfall (Guffanti et al. 2008), DDS all feature complete closure at low ashfall thicknesses (≤1 mm). Bariloche airport officials also closed the airport at the first sign of ashfall, as has occurred after other eruptions in the last 35 years (Tables 7 and 8). DDS both predicted that runway surfaces would suffer some degradation at the thicknesses received in Bariloche, however the extent to which this occurred is unknown as the runway was replaced soon after the eruption. As the runway was scheduled for resurfacing in March 2012, officials chose to bring this forward to October 2011 to take place during the existing disruption due to continued hesitance of airlines to use Bariloche Airport. Due to the majority of airports following standard procedures for total shutdown in ashfall, the DDS are assessed as accurate predictors of impacts in the CC-VC ashfall event (Table 11).

Telecommunications

The most reliable form of communication throughout the emergency was radio (VHF and UHF). In Bariloche, radio amateurs were instrumental in relaying information. Cellphone networks experienced problems due to overloading of networks. There were anecdotal reports of cell signal attenuation caused by airborne ash and equipment failure caused by deposition of ash onto

Table 10 Pre-event and post-event mitigation strageties for critical infrastructure sectors in the three main urban areas affected by ashfall

Infrastructure	Towns	Pre-event planning	Mitigation	Recovery strategies
Electricity	Villa la Angostura	Some ashfall planning, mosly around the cleaning of lines	Fire trucks deployed to wash insulators; Increased insulator pin length from 250 mm to 500 mm (initially in locations prone to flashover, but eventually all 3,500 insulators were changed)	Cleaning insulators; increase insulator pin length
	Bariloche	Some ashfall planning, mosly around the cleaning of lines	20 MW diesel generation plant installed for back-up supply (usual demand 45–55 MW so some shortfall); fire crews rinsed insulators	Cleaning insulators; generator use
	Jacobacci	No ashfall specific planning	Switches required ongoing replacements (for months after the eruption); volunteer firefighters washed lines after the eruption and severe remobilisation events (however due to ash remaining dry because of the lack of rainfall flashover risk was reduced)	Cleaning insulators; replacement of switches
Water Supply	Villa la Angostura	Planning for stream blockages (army brought in to clear these)	Drilled a groundwater well ~21 m deep (not treated and distributed via gravity fed system) to make up for the short fall due to issues with stream blockages and pump maintenance issues; pumps that were abraided by ashfall were replaced	Replacement of pumps/pump components; new groundwater well drilled
	Bariloche	No ashfall specific planning	Sand filters neded to be cleaned more frequently than the pre-eruption routine which was for one sand bed out of rotation for cleaning every ten days; generators prioritised for running pumps to treatment plant, however the demand (2 MW) exceeded the capacity of the generator trucks (1 MW per truck)	Replacement of pumps/pump components; cleaning of filtration mechanisms
	Jacobacci	No ashfall specific planning	A new well was dug to to cover the increased demand due to the eruption	New groundwater well drilled
Infrastructure	Towns	Pre-event planning	Mitigation	Recovery strategies
Waste water	Villa la Angostura	No ashfall specific planning	-	-
	Bariloche	Some planning but only to itry prevent ash from getting into system initially	Some discharge of untreated wastewater was made into the lake as the system became overwhelmed; municipal crews dug ash out of catchpits to try prevent ash getting into the system; manually moved generators around the system to keep wastewater moving; pump impellers replaced every six months rather than 12	Discharge of untreated wastewater into lake; replacement of pump components
	Jacobacci	No ashfall specific planning	-	-
Roading	Villa la Angostura	Some ashfall planning but underestimated the amount of ashfall and the number of trucks required	Route 231 and the main roads within the town were cleared by bulldozers the day after the eruption; water tankers were used to dampen down ash and prevent remobilisation	Bulldozing and sweeping roads clear; dampening down ash; cleaning air filters more frequently
	Bariloche	Some ashfall planning but underestimated the amount of ashfall and the number of trucks required	Main roads began to be cleared of ash by municipal authorities within hours of eruption; road sweepers were deployed for smaller ashfall events	Bulldozing and sweeping roads clear; dampening down ash; cleaning air filters more frequently
	Jacobacci	Some ashfall planning, but not specific amounts and equipment	Speeds reduced to 20 km/h on days where ashfall was being remobilised; municipal water trucks dampened down ash on roads; ash removal and clean up focussed on main roads and reopening link to Bariloche	Bulldozing and sweeping roads clear; dampening down ash; cleaning air filters more frequently
Airports	Bariloche	Some ashfall planning	Did not receive official warning so no prior actions could be taken; ashfall was placed into hollows and dips in the surrounding land and then vegetated to prevent remobilisation; an extensive irrigation system was also installed to keep ash from remobilised onto the runway	Removal of ash; dampening down of ash; permanent irrigation system installed

Table 11 Comparison of PCC-VC ashfall impacts to infrastructure with existing damage state scales

Infrastructure	Town	Ash thick-ness (mm)	Damage State from thickness (Wilson et al. 2014a)	Damage state description	Damage state based on obser-vations	Justification of assigned damage state	Damage state from thickness (Jenkins et al. 2014)	Damage state description	Damage state based on obser-vations	Justification of assigned damage state
Electricity	Villa la Angostura	150–170	3	Damage: structural damage to transmission equipment; Disruption: widespread disruption to supply with some permanent issues	2	No reported issues with structural damage, no permanent disruption	5	Damage: structural damage; Function: permanent disruption	3–4	No reported issues with structural damage, no permanent disruption
	Bariloche	30–45	2	Damage: damage to exposed moving parts, possible line breakages; Disruption: flashover, cleaning and repair	1	No damage reported to lines or parts	3–4	Damage: some damage to components; Function: disruption requiring repair	3–4	~
	Jacobacci	50	2		2	~	3–4		3–4	~
Water Supply	Villa la Angostura	150–170	3	Damage: infilling of open reservoirs and tanks, collapse of reservoir roofs; Disruption: severe contamination of water supply and exhaustion of supply due to demand	2	No roof collapse reported, water demand raised but not exhaused	Not included in damage states due to issues with relating impacts to a single hazard intensity measure (in this case ash thickness (mm)			
	Bariloche	30–45	2	Damage: damage to pumping equipment, infilling of tanks; Disruption: contamination of water, increased treatment needed	2	~				
	Jacobacci	50	2		0	No damage due to pumps being in pumphouses				
Waste water	Villa la Angostura	150–170	3	NA	NA	NA	Not included in damage states due to issues with relating impacts to a single hazard intensity measure (in this case ash thickness (mm)			
	Bariloche	30–45	2	Damage: sedimentation causing some blockages and damage, possible infilling of tanks; Disruption: temporary disruption to clean network, possible release of untreated sewage	2	~				
	Jacobacci	50	2	NA	NA	NA				
Roading	Villa la Angostura	150–170	3	Damage: complete burial, structural damage to bridges; Disruption: roads impassable, widespread closures	2	No structural damage reported, some vehicles could use roads at limited speeds	4	Damage: road surface abrasion; Function: 4WDs obstructed	4	~
	Bariloche	30–45	1	Damage: possible abrasion of road markings and paved surfaces; Disruption: reduced visibility and traction	1	~	3	Damage: road surface and marking abrasion; Function: 2WD vehicles obstructed	2	Some vehicles could use roads at very limited speeds
	Jacobacci	50	2	Damage: possible abrasion of road markings and surfaces; Disruption: reduced traction, closures	2–3	Remobilisation of the ashfall deposit meant that roads were impassable some days	3		3	~
Airports	Bariloche	30–45	2	Damage: moderate abrasion of runway and landing lights; Disruption: airport closure	2	~	1–4	Damage: possible runway degradation; Function: runway closure	1–4	~

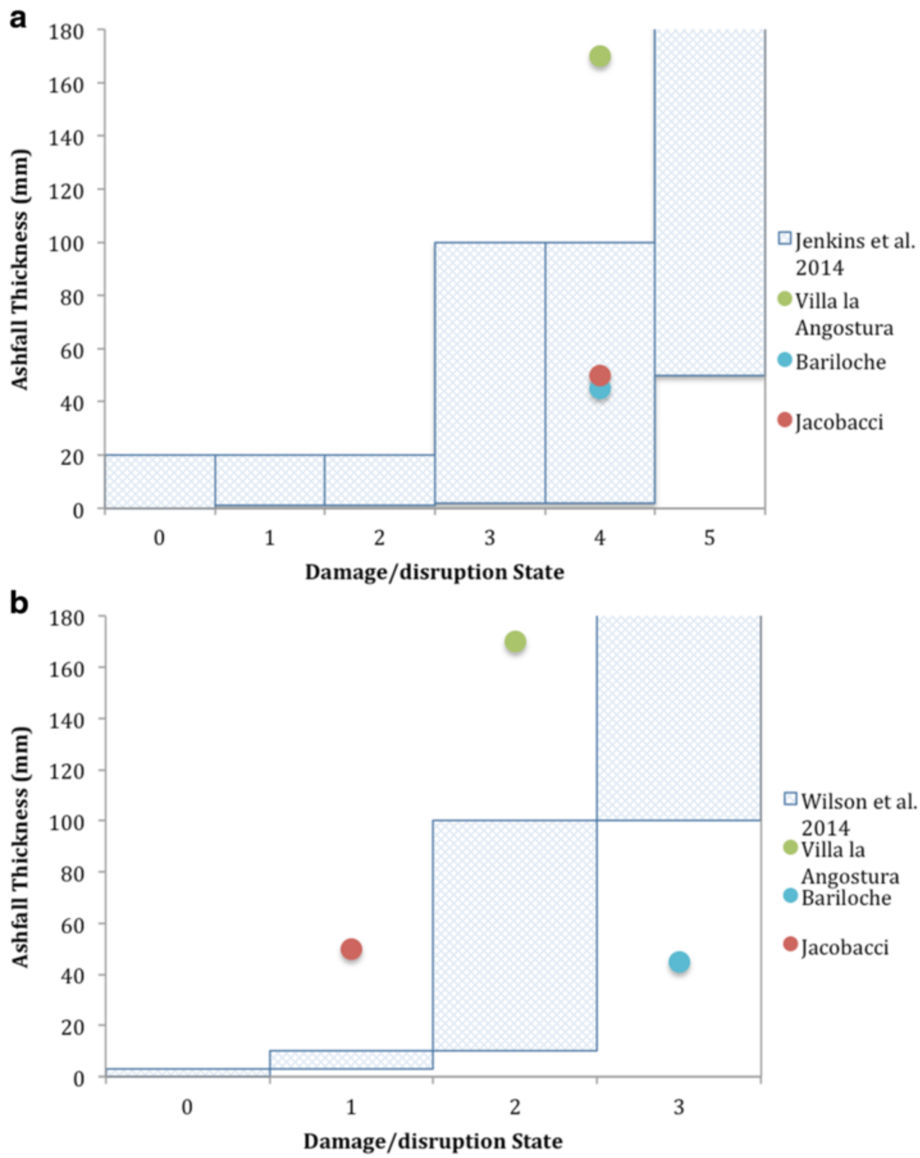

Fig. 7 Observed damage states for the electricity network across the three main urban centres, compared to hazard intensity ranges given with the **a** Jenkins et al. 2014 and **b** Wilson et al. 2014a damage state schemes

ground equipment such as cell phone exchanges, but this was difficult to verify. The 12-hour battery life of antennae came close to being exhausted during the power outages. However, as there was no real damage or widespread disruption to networks due to the ashfall, available DDS (Wilson et al. 2014a) were not applied to this sector.

Urban clean-up

The removal of ash from streets, public places, business and residential districts was a major focus of the emergency management and recovery effort. In Villa la Angostura sixteen houses suffered roof collapse, and 40 more were braced to prevent roof collapse. The municipality and wider community undertook a fast and efficient clean-up response. The initial focus was on cleaning the main roads. On the 7 June 2011, 40 km of the main highway (Ruta 231) was closed and cleared with bulldozers then dampened with water tankers (Fig. 15 a). Ash removed by residents with help from volunteer brigades was placed on roadsides then collected by the municipality and taken to provisional ash dumps, located in each neighbourhood. Material from the dumpsites was then rapidly transferred to an old quarry located in Puerto Manzano (Fig. 15 b). At this main dumpsite, compaction and stabilisation of the ash

Fig. 8 Villa la Angostura water supplies **a** non-operational sand filters of the Las Piedritas stream-fed system, filled with ashfall; **b** operational sand filters at the Las Piedritas treatment site; **c** Lomas del Correntoso intake from Lake Correntoso; **d** Chlorination plant

was undertaken. A further focus of clean-up efforts in Villa la Angostura has been the clearing of natural dams higher up the streams that flow through the town. This was done in an attempt to mitigate the lahar risk as it was thought that the dams could cause the build-up of ash followed by catastrophic failure. Army teams were deployed to cut and clear debris.

Bariloche received up to 45 mm of ash fall, which equates to approximately 1,500,000 m^3 across the urban area. The city did not have sufficient heavy earth-moving machinery for clean-up, and had to hire external machinery and utilise private vehicles. The first area to be cleared was the inner central business district. Clean-up of the city took two months with costs estimated to be some $USD 35 million, not including business disruption losses. Residents were encouraged to focus on clearing their own properties and were asked to create just one pile of material per city block to facilitate removal by the municipality. Municipality efforts lasted until December 2011. There were high rates of volunteerism in cleaning the town, particularly in 'high value' areas such as the downtown area important to tourism, and outside schools and hospitals. Most of the collected material (ash and other urban waste) was disposed of in the old municipal quarry located on the southern fringe of the city. This dump was quickly filled (Fig. 16) so new disposal sites were selected. The most important were close to a municipal gas plant where material was accumulated in piles and covered with soil to prevent wind remobilisation; and the municipal dumping site for waste from forestry activities. During the first two days of ash fall some ash was also dumped in the lake both in Villa La Angostura and Bariloche.

In Jacobacci, clean-up operations were delayed for a week because of extremely poor visibility. The main streets were cleared first, using all available trucks, diggers and bulldozers in the town (Fig. 17a). Following this, residents were provided with large sacks to fill with ash cleared from their own properties (Fig. 17b, c, & d). Collected ash was dumped in natural depressions to the east (downwind) of the town, and weighed down with waste building materials in a short-term attempt at stabilisation. In the longer term, there were plans to vegetate the deposits. Clean-up operations in Jacobacci were significantly more difficult by constant problems with wind remobilisation of unconsolidated ash deposits, not only within the urban area but also from upwind sources. This meant that clean-up operations had to be coordinated and carried out numerous times following every major wind storm tephra remobilisation event.

Clean-up of the ashfall had an immediate effect on the impacts to critical infrastructure that the urban centres were undergoing as a result of the ashfall. Organised and proactive cleaning of power lines and insulators in Villa la Angostura meant that while many flashover events occurred the network still remained functional after a

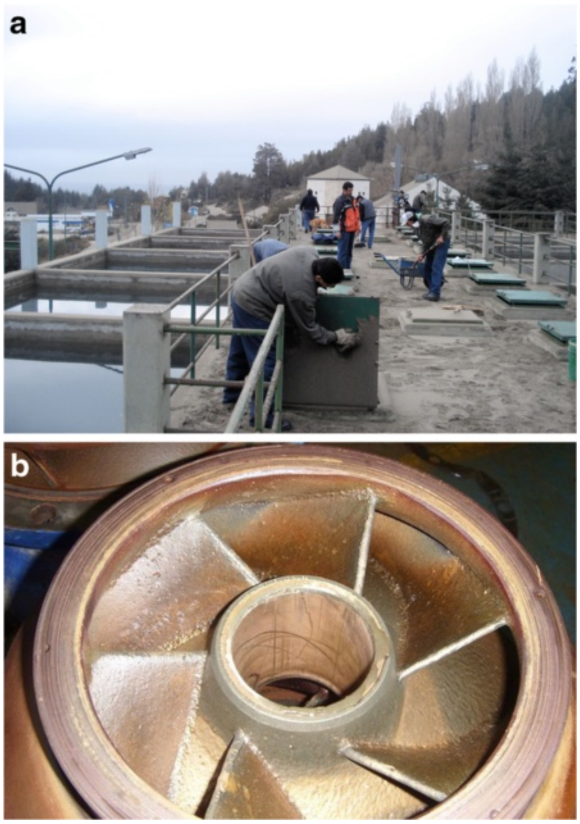

Fig. 9 Bariloche water treatment plant **a** people cleaning out open air sand filters after the ashfall; **b** pump impeller showing some accelerated abrasion due to ash

few days of ashfall. Similarly, at the water treatment plant in Bariloche, rotational cleaning of sand filters (one sand bed taken out of use for thorough cleaning every ten days) was effective, and despite supplies being stretched the system mostly coped. Urban clean-up is the most effective mitigation tool available to emergency managers and allows for rapid restoration of critical infrastructure services (Hayes et al. *in prep*).

Previous assessments of urban tephra fall clean-up have shown that urban areas with large tephra fall accumulation will remove the majority of the tephra material, whereas areas with lower accumulation will remove a smaller proportion of this (Hayes et al. 2015). This trend was not shown after the CC-VC event, where clean-up in Villa la Angostura removed approximately 20,000 $m^3$of tephra per km^2 (although tephra fall accumulation was ~300,000 m^3/km^2), compared to Bariloche where a similar amount of material was removed (~15,000 m^3 of tephra per km^3) despite experiencing much lower tephra accumulation (~35,000 m^3/km^2) (Hayes et al. 2015). Although amounts of tephra fall material collected and dumped in Jacobacci are not known, it is likely that this would have been low regardless of tephra fall accumulation amounts, as continued wind remobilisation meant clean-up operations were needed repeatedly and focussed mainly on essential areas such as main roads and schools. Tephra fall accumulation thresholds for clean-up actions are proposed by Hayes et al. (2015), the accumulation for Bariloche and Jacobacci compares relatively well with the predicted and actual clean-up actions (Figs. 2 and 18). Whilst this is a relatively generalised scale it still provides some indication as to the different actions taken. This shows that although the actions taken correlate well with the categories suggested by Hayes et al. (2015), the amount of tephra actually

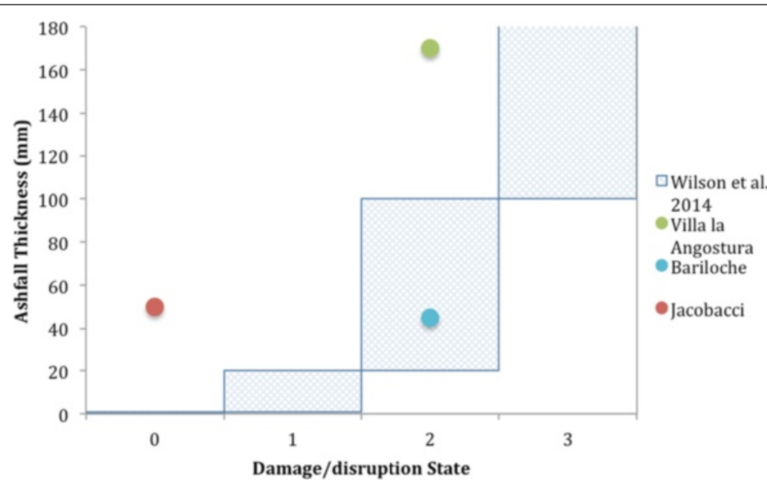

Fig. 10 Observed damage states for the water supply network across the three main urban centres, compared to hazard intensity ranges given with the Wilson et al. 2014a damage state scheme

Fig. 11 Bariloche wastewater treatment system **a** biological reactor showing some Nocardial foaming; **b** and **c** sewer lines and junctions inundated with ash; **d** ash-accelerated pitting and thinning damage to sewage pump impeller

Fig. 12 Road conditions in Jacobacci **a** poor visibility In Jacobacci (11/7/2011); **b** 2WD car outside Jacobacci in ~50mm ash; **c** car air filter clogged with ash; **d** sticker on car window in Jacobacci advising drivers to restrict their speed to 20km/h in order to not "stir up the ash." (Photo credit: Ailen Rodriguez)

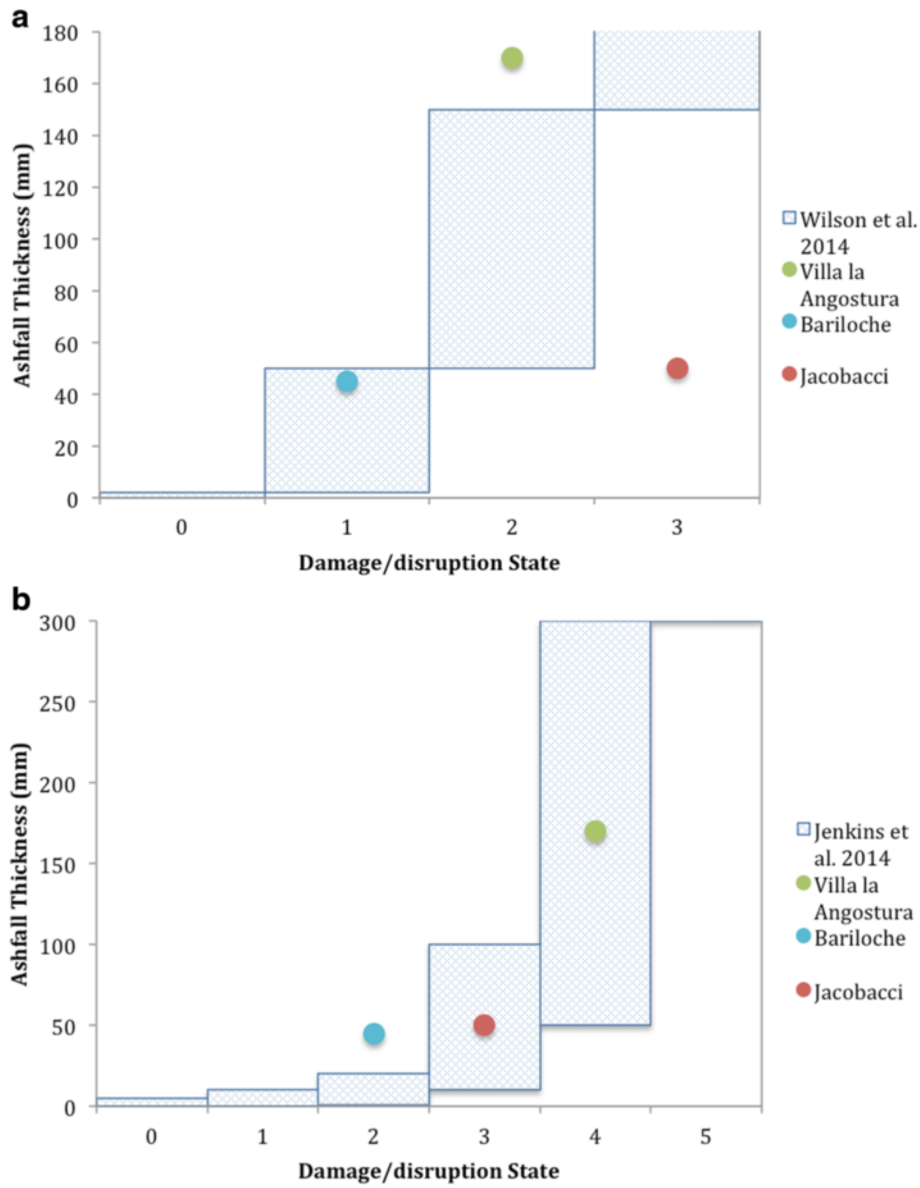

Fig. 13 Observed damage states for roading across the three main urban centres, compared to hazard intensity ranges given with the **a** Jenkins et al. 2014 and **b** Wilson et al. 2014a damage state schemes

removed and dumped comprises a smaller percentage of the total tephra accumulation than expected based on previous events. There are a number of possible explanations for this, including that tephra dumping was not always undertaken using official guidelines or well recorded or that residents in the area were relatively tolerant to tephra on private properties.

Discussion

The most notable aspect of the ashfall impacts from the 2011 CC-VC eruption was the divide between the temperate region (including Villa la Angostura and Bariloche) and the semi-arid steppe (including Jacobacci). Despite receiving smaller ashfall thicknesses, the impacts in the steppe region were more severe than the temperate zone. This is due to the unique environmental conditions that caused extreme, prolonged wind remobilisation of the ashfall deposit. This caused conditions similar to those at the time of deposition over the period of many months leading to prolonged disruption to infrastructure and primary industry. This was similar to the more severe impacts in the steppe area after the 1991 Hudson eruption,

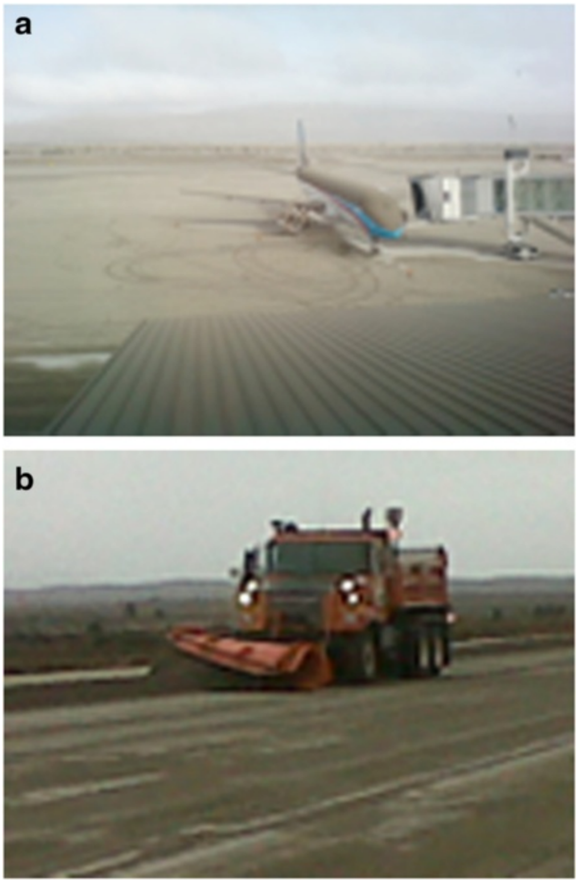

Fig. 14 Bariloche airport **a** ash covered plane immediately after the initial ashfall; **b** clean up beginning with bulldozers removing ash from the runway (Photo credit: Bariloche Airport)

Fig. 15 Photographs showing the Villa la Angostura urban clean-up measures **a** Water tanker spraying water along main road to dampen down ash (March 2012); **b** Puerto Manzano quarry ash dump (March 2012)

where wind remobilisation and 'ash storms' slowed recovery over many years (Wilson et al. 2011b). In contrast, the thicker, coarser deposits in the temperate zone stabilised relatively rapidly, meaning that recovery could begin within weeks of the ashfall events. This created two distinct areas of impacts and recovery times, which required different management and mitigation strategies.

Overall, the majority of the CC-VC impacts were similar to those experienced after previous ashfall events, especially compared to the 1991 Hudson and 2008 Chaitén eruptions that also took place within the Patagonian region (Tables 7 and 8). However, when comparing impacts to agriculture and infrastructure to thickness thresholds placed on DDS scales, the temperate region of Nahuel Huapi National Park, and Villa la Angostura and Bariloche townships consistently had fewer severe impacts than expected under high thicknesses of ashfall (>150 mm in Villa la Angostura and >30 mm in Bariloche)(Tables 5, 6, 11, 12, 13). Impacts mainly resulted in infrastructure disruption rather than long-term damage, and most sectors recovered with the

Fig. 16 Compacted ash dumpsite on outskirts of Bariloche. Previously there was a small depression that was filled by the dumpsite

Fig. 17 Ash removal from main street of Jacobacci (9/6/2011); **a** Bulldozer removing ash from the main street; **b** Residents sweeping dry ash off roofs with brooms; **c** Piling ash into collection piles on the road for municipal collection; **d** People cleaning ashfall from a community playground. Photo credits: Ailén Rodriguez (**a**) and Jose Mellado (**b**, **c**, **d**)

removal of ash and minimal intervention and repairs. If the damage predicted by ashfall thicknesses had occurred recovery would have taken months to years, and financial losses to the region would have been more severe. This is likely due to the damage state thresholds not accounting for mitigating factors (such as the high rainfall levels hastening the incorporation of ash into the soil, preventing remobilisation, and rinsing infrastructure such as electrical systems and roading), which resulted in the higher resilience to ashfall in Villa la Angostura and Bariloche. An unexpected outcome was the matching of observed impacts in the Jacobacci and steppe

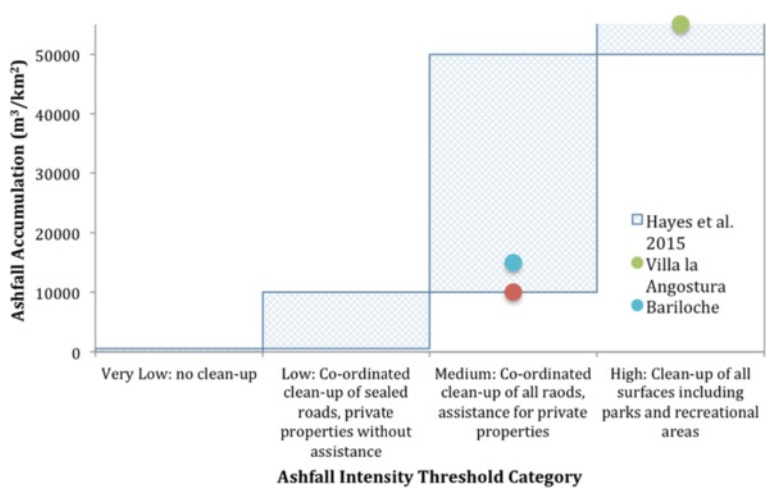

Fig. 18 Clean-up thresholds with damage thicknesses from Hayes et al. 2015, compared to actual clean-up actions and tephra accumulation in the three main centres affected by the 2011 PCC-VC ashfall

Table 12 Summary of how key infrastructure systems performed compared to damage states assigned based on tephra thickness thresholds

		Villa la Angostura	Bariloche	Jacobacci
Electricity	Wilson et al. 2014a	Better	Better	Same
	Jenkins et al. 2014	Better	Same	Same
Water	Wilson et al. 2014a	Better	Same	Better
	Jenkins et al. 2014	NS	NS	NS
Waste water	Wilson et al. 2014a	NI	NI	NI
	Jenkins et al. 2014	NS	NS	NS
Roading	Wilson et al. 2014a	Better	Same	Same
	Jenkins et al. 2014	Same	Better	Same
Airports	Wilson et al. 2014a	NI	Same	NI
	Jenkins et al. 2014	NI	Same	NI

NS: Denotes where no damage state scheme was developed
NI: Denotes where sites were not investigated during this study

region, with those predicted by the ashfall thickness thresholds associated with the DDS (Tables 5, 6, 11, 12, 13). As the extreme climate (very low precipitation, <150 mm/year) resulted in the nature of the impacts being largely determined by the severe wind remobilisation, it is unlikely that temperate areas would have the same impacts at similar ashfall thicknesses. This could restrict the application of the hazard thresholds to future events that do not undergo substantial wind remobilisation.

A limitation of this study is the relatively small number of interviews undertaken and the assumption that the information collected during the post-EIA is representative. This was accounted for by including interviews with municipal level staff, these gave insight into broad municipal and regional level trends. Interviews with individual farmers and stakeholders correlated well with these regional scale interviewees.

Another factor that determines the DDS of a sector is the emergency response actions taken by managers or stakeholders after the event. The schemes, integrate management decisions into the impact descriptors, meaning that decision-makers can influence the DDS, independent of the actual thicknesses received. This is particularly evident when considering roading impacts, where road closures and types of cars on the road are considered. In areas where ashfall has occurred before or the event is prolonged over many months, such as in the steppe region of this case study, emergency managers may be less likely to close roads and drivers more confident of their ability to drive on them compared to a region that had not experienced significant ashfall before. For example after the 2012 Tongariro eruption in New Zealand, the main state highway in the area was closed following <3 mm of ashfall (Jolly et al. 2014; Leonard et al. 2014). In contrast, roads remained open in the Bariloche and Jacobacci regions, despite receiving up to 50 mm of ashfall. This different risk tolerance can impact which DDS a sector falls under, independent of the hazard intensities that occurred.

Table 13 Summary of how agricultural systems performed compared to damage states assigned based on tephra thickness thresholds

		Nahuel Huapi National Park	Steppe region
Agriculture	Wilson et al. 2009	Better	Better
	Jenkins et al. 2014	Same	Same

NS: Denotes where no damage state scheme was developed
NI: Denotes where sites were not investigated during this study

The utility of DDS and their associated hazard intensities as a pre-event predictive tool is limited by a number of factors. Pre-EIA aim to forecast the effect that a hazardous event will have on an exposed system usually through a qualitative assessment, unlike risk assessments that have numerical probabilities attached to them. As impact is defined as a function of the hazard, and the exposed assets and their vulnerabilities (ISDR 2009), pre-EIA need to incorporate information on all these elements. Therefore, applying the DDS on hazard maps or models can be challenging, as they only take into account one hazard intensity measure (thickness) and do not consider the design or vulnerability of the exposed assets, or if any mitigation measures that may minimise losses are in place. Another possible limitation of using the states as a forecasting method is that they are based on information that has been collected from various events during the limited number of available post-EIA.

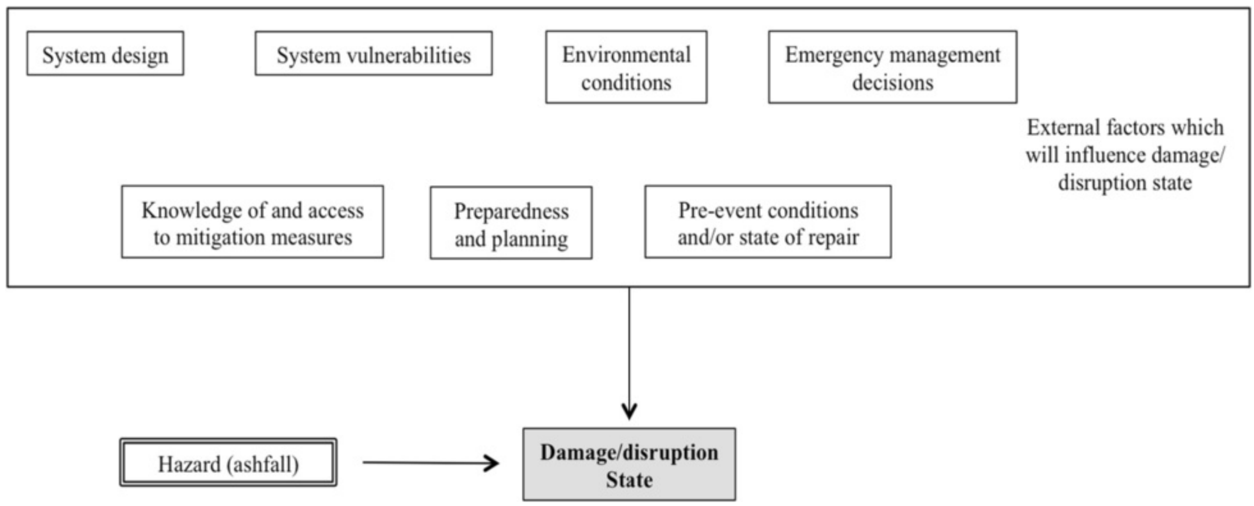

Fig. 19 Diagram of factors that can contribute to the observed damage/disruption state, external to the ashfall deposit characteristics

This means that they are likely to have been taken from information that will be biased towards the more extreme impacts, as assessment teams often look to assess impacts and damage rather than resilience. This could be a possible explanation for why the temperate region (Villa la Angostura and Bariloche) was not affected by the high severity impacts predicted, whereas the semi-arid region (Jacobacci) which was much more vulnerable than many other areas worldwide, received the impacts forecasted by the states. Current post-EIA research is moving towards eliminating this bias by adopting guidelines used after other hazards that recommend statistically robust assessment methods, such in as tsunami research (Chagué-Goff et al. 2012; Szczucinski et al. 2006; Wilson et al. 2014b). However, despite these limitations, in the absence of further information the thresholds have shown, using the CC-VC case study and others that they give some guidelines as to what possible impacts will manifest.

One of the most useful applications of the DDS scales is to quantify observations taken during post-EIA. This allows qualitative statements to be placed into a framework suitable for comparisons and trends across different affected areas to be assessed. This application is similar to how the Modified Mercalli (MM) scale (Wood & Neumann 1931) and the more recent European Macroseismic Scale (EMS)(Musson et al. 2009) are used to describe damage and human experience during an earthquake. As with volcanic ash DDS, there have been a series of attempts to accurately assign hazard intensities to each scale. For these scales research has focussed on matching the scales with ground acceleration, velocity and displacements (Lliboutry 1999; Wald et al. 1999). Although, the assumptions necessary to calculate the corresponding hazard intensities mean that other risk assessment methods, such as numerical modelling of specific repair costs with hazard intensities, are still preferable forecasting tools (Rossetto et al. 2014). Volcanic risk assessments lack the strong empirical dataset that earthquake research possesses (Wilson et al. 2014a), therefore hazard thresholds and damage descriptors based on 'expert judgement' are often the only available predictive tool. This means that continued refinement of hazard thresholds and the incorporation of vulnerability information and other factors external to the ashfall into schemes (Fig. 19). This could mean that a different set of thresholds will need to be identified for different climatic regions, system types and design, and possibly other vulnerability characteristics in order to refine pre-event impact assessments.

Towards universal damage/disruption state schemes

In order to predict the impacts (or DDS reached) to a system the understanding the hazard and its intensity (e.g., ashfall thickness) is vital. However, an understanding of the vulnerability of the affected system is also needed (Alexander 2002). This includes contextual information such as systems design, the pre-existing condition and maintenance, and the season and climatic zone the ashfall was deposited in. This means that any hazard intensity thresholds placed on DDS or impact classification schemes need to be tailored for specific regions and infrastructure and primary industry types.

Despite the challenges of incorporating systems with different vulnerabilities, the pursuit of a set of DDS that can be universally applied after volcanic ashfall, both as a forecasting tool and a means of categorising damage during post-EIA, has continued for many years. The infrequent nature of large volcanic eruptions and variations in eruption types, characteristics and areas affected means that there will always be challenges in creating a universal systems based on data aggregated from across different events. Therefore, whilst it is unlikely that a scheme that can be universally applied to all scenarios is possible, there are some considerations that need to be taken into account during future refinement and development. These include:

- The creation of different DDS schemes for different infrastructure designs and agricultural types is needed. The specific properties that DDS schemes were designed for should be outlined in accompanying material so that they can be used with caution for different systems. This is especially pertinent when considering water and wastewater systems that have high, and location-dependent, variability in their design.
- Numerous factors external to the ashfall deposit characteristics will also influence the impacts to critical infrastructure and agricultural systems (Fig. 19). These factors need to be considered when creating and refining DDS. It is likely that different hazard intensity thresholds (in this case ashfall thicknesses) for each DDS will need to be identified for different systems designs and environmental conditions.
- When considering critical infrastructure, there should be an increasing emphasis on the refinement and standardisation of existing schemes, rather than the creation of new ones. Both the Jenkins et al. 2014 and the Wilson et al. 2014a schemes provide sufficient framework for refinement of thresholds and descriptors as more empirical and analytical data becomes available. This allows for more accurate thresholds to be assigned and is more beneficial to the field than the continued development of new schemes.
- DDS developers need to acknowledge two main uses for the schemes (forecasting tools during pre-EIA and as a method of categorising impact information during post-EIA) and incorporate instructions on how best to apply the states in each scenario.
- The distinction between damage and disruption (or functionality) needs to be clearly outlined and defined.
- A strength of the Jenkins et al. 2014 scheme is that the ashfall thicknesses associated with each state are given as a range which overlaps with the thicknesses given for the previous state. This is likely to be more accurate when applied to case studies, as it is unlikely that there would be a vast jump in damage and/or disruption due to an extra millimetre of ash being deposited on an area, rather there would be a gradual increase in damage with increasing ashfall thickness. This approach also better accounts for the variation in impacts across areas, even when similar ashfall thicknesses are measured.
- Continued application and validation of DDS schemes to case studies is necessary to improve accuracy of hazard thresholds and associated descriptors. This needs to be undertaken in a variety of settings for all infrastructure and agricultural sectors. Additionally, assessment by researchers not involved in the development of the DDS is advantageous to proving repeatability and usability.

Conclusions

Overall, ashfall impacts to infrastructure and agriculture after the 2011 CC-VC eruption were broadly similar to impacts observed elsewhere after comparable ashfall events. This event was notable, however, due to the contrasting impacts, management, and recovery between the two climatic regions. Severe wind remobilisation in the semi-arid steppe region (including the town of Jacobacci) meant although ashfall thicknesses were much lower, the DDS observed were often the same as those experienced in areas more proximal to the volcano that received much greater ashfall thicknesses. Conversely, impacts were minimised and recovery aided by the temperate environment and management response in Villa la Angostura and Bariloche. This climatic division of impacts has been recorded elsewhere, notably after the 1991 Hudson eruption (Wilson et al. 2011a).

Application of DDS by their associated hazard intensity thresholds (ashfall thickness) showed a relatively good correlation of impacts with thicknesses for the Jacobacci and semi-arid steppe region (except for water systems which performed better than predicted by the DDS)(Tables 12 and 13). This was unexpected due to the unique conditions and extreme wind remobilisation. The temperate region (including Villa la Angostura and Bariloche) underwent less severe impacts than ashfall thicknesses indicated, with critical infrastructure networks mostly returning to full functionality within weeks of the initial event. This indicates the limitations of using DDS as the sole predictor of impacts and suggests refinement of hazard thresholds and increased consideration of system types and design, and environmental and vulnerability characteristics is required.

Abbreviations

CC-VC: Cordón Caulle – volcanic complex; DDS: damage/disruption states; EIA: event impact assessment; WTP: water treatment plant.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

HC, TW, and CS planned and conducted the research. HC prepared the initial manuscript with substantial input from TW and CS. CS led the sections on water supplies and waste water. VO, GV, and PB helped design and conduct interviews, and contributed vital discussion points regarding the interpretation of field data. All authors read, reviewed and approved the final manuscript.

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