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ORIGINAL PAPER

Agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America

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Abstract Agricultural production is often concentrated in volcanically active or previously active areas where weathered volcanic products form fertile soils. However, this proximity means agriculture is exposed to tephra fall hazards. The type and severity of impacts to agricultural systems from tephra fall are dependent on both the hazard intensity metrics (tephra fall characteristics, such as thickness, grain size) and the vulnerability characteristics of the exposed agricultural system(s). Understanding the relationship between significant intensity metrics of tephra fall hazard and farm-scale and region-scale vulnerabilities is key to impact assessment and informing management and recovery strategies. Several large silicic eruptions have occurred over the past 20 years in the Patagonian region of South America, including the 1991 Hudson, 2008 Chaitén, and 2011 Cordón Caulle eruptions. These events deposited varying thicknesses of tephra on thousands of farms distributed across a variety of climates and production styles. Drawing on impact assessment data collected from interviews undertaken on post-event impact assessment reconnaissance trips, and other reports, this study evaluates the importance of tephra thickness as a hazard intensity metric, and vulnerability characteristics, when assessing impacts in the short and long term and, compares the effectiveness of response and recovery strategies. Whilst tephra thickness was the best single indicator of agricultural

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production losses, other factors, notably climate, farm type, and access to mitigation measures such as irrigation and/or cultivation, were also important indicators of damage. The climatic zone and associated precipitation level was found to be one of the most important characteristics of vulnerability, with higher damage occurring at lower tephra thicknesses in the semi-arid regions compared to farms in the temperate zone.

Keywords Tephra fall · Agriculture · Tephra impacts · Impact assessment · Management · Cordón Caulle-volcanic complex · Chaitén · Hudson

1 Introduction

Global population growth places increasing pressures on maintaining and increasing food production from agricultural systems (Godfray et al. 2010). Production is often concentrated in volcanically active areas where weathered volcanic products form fertile soils (Shoji et al. 1993). Tephra fall is one of the most common hazards from an explosive volcanic eruption and can cover thousands of square kilometres of agricultural land, potentially reducing agricultural production (Blong 1984). Tephra fall can have both direct (i.e. physical and chemical effects to crops, livestock, and soils, Table 1) and indirect effects to agricultural production (i.e. due to disruption of electricity supply, transport networks, and water supplies) (Neild et al. 1998; Wilson and Cole 2007). The high exposure and potential consequences of tephra fall for agriculture mean that an understanding of the impacts that can occur and their likelihood, magnitude, and duration is vital to managing the risk.

Risk and impact assessments (terminology is defined in Table 2) are approaches that can deterministically or probabilistically forecast potential consequences, depending on the desired outcome. They can be used to inform the development of risk mitigation and preparedness strategies before an eruption and inform damage assessment, emergency response, and recovery strategies after an eruption occurs to minimise losses. In the case of volcanic hazards, risk and impact assessment is a rapidly developing field, but there are few fully developed open-source models available (Sparks et al. 2013). There have been considerable advances in tephra fall hazard modelling occurring over the past two decades (e.g. Biass et al. 2014; Bonadonna et al. 2005; Jenkins et al. 2012; Macedonio et al. 1988; Magill et al. 2006), and tephra fall impacts to agriculture are also largely known, and their causes well constrained qualitatively (Cronin et al. 1998; Wilson et al. 2011a, b; Jenkins et al. 2014a, b). However, there has been less progress on developing fully integrated tephra impact and quantitative risk models for agriculture which relate hazard intensity to impact, with a key constraint being the lack of quality impact and vulnerability data (Jenkins et al. 2014a; Wilson et al. 2009). Several studies have presented models which relate tephra fall thickness or load (kg/m^2) to agriculture impacts; these are informed by post-event impact assessments (post-EIA) observations and expert judgment (Blong 1984; Wilson and Kaye 2007; Jenkins et al. 2014b). These studies all acknowledge they are relatively simplistic and are based on small samples of empirical data. Post-event impact assessments (Post-EIA) (Sword-Daniels et al. 2011; Wardman et al. 2012; Wilson et al. 2007, 2011a, 2012a, b) and empirical laboratory studies (Cronin et al. 1998; Wilson et al. 2009) have been used to fill this void (Wilson et al. 2011a, b; Wilson et al. 2014; Jenkins et al. 2014a, b).

Table 1 Reported physical and chemical impacts to soil, vegetation, and animal health at (A) thin (0–10 mm); (B) moderate-to-thick (10–500 mm); and (C) very thick (>500 mm) tephra fall depths

	Physical impacts	Examples and references	Chemical impacts	Examples and references
(A) Thin ashfalls (0–10 mm)				
Soil	Tephra permeability can influence soil gas and water exchange	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981)	Increasing soil acidity due to tephra leachates, usually minor and/or short term	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris and Delmelle 2012; Ugolini and Dahlgren 2002; Zheng 2010)
	Cementation of tephra can further reduce water infiltration and gas exchange.	Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al. 2012b); Mt. St Helens (Cook et al. 1981)	Can add beneficial amounts of some elements in some cases (where a deficiency is present)—particularly sulphur and potassium	Ruapehu (Cronin et al. 1997, 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas 1990)
	Radiation can be reflected lowering the soil temperature	Mt. St Helens (Cook et al. 1981); Others (Ayris and Delmelle 2012; Smith et al. 2010)	Addition of elements from environmentally available soluble salts coating tephra and more slowly soluble elements, such as fluoride, aluminium, and chloride	Review paper (Ayris and Delmelle 2012)
Vegetation	Photosynthesis prevented due to covering of leaves with tephra Abrasion of vegetation due to tephra particles (primary and remobilised)	Merapi (Wilson et al. 2007); Mt. St Helens (Antos and Zobel 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011a); Puyehue-Cordón Caulle (Wilson et al. 2012b)	Chemical burns to leaves and fruits due the acidity of tephra	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996)
Animal Health	Tooth abrasion leading to trouble with grazing and premature ageing Eye irritation	Hudson (Wilson et al. 2011b): Puyehue-Cordón Caulle (Flueck 2013; Wilson et al. 2012b); Paricutin (Rees and Angeles 1970)	Low risk of fluorosis but unlikely at these thicknesses	Cronin et al. (2003)

Table 1 continued

	Physical impacts	Examples and references	Chemical impacts	Examples and references
(B) Moderate–thick ashfalls (10–500 mm)				
Soil	Tephra thick enough to form a barrier between soil and the atmosphere. Preventing soil, water, and gas exchange	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981); Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al. 2012b); Ruapehu (Cronin et al. 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas 1990); Others (Ayris and Delmelle 2012; Smith et al. 2010)	As for thin ashfalls (Table 1a). Larger quantities of soluble elements may be available, but may need to be cultivated into soil to have positive effect	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris and Delmelle 2012; Ugolini and Dahlgren 2002; Zheng 2010)
Vegetation	As for thin ashfalls (Table 1a) Complete burial of the plant structure causing plant death Overloading of plant causing breakages	Merapi (Wilson et al. 2007); Mt. St Helens (Antos and Zobel 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011a); Puyehue-Cordón Caulle (Wilson et al. 2012b)	As for thin ashfalls (Table 1a) Leachable elements may provide immediate stimuli to plant growth	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996) Soil (Kabata and Pendias 2001; McLaren and Cameron 1996; Shoji et al. 1993); Aerosols (Camuffo and Enzi 1995; Decker and Christiansen 1984; Frognerkockum et al. 2006; Nelson and Sewake 2008; Phelan et al. 1982; Smith and Staskawicz 1977)

Table 1 continued

	Physical impacts	Examples and references	Chemical impacts	Examples and references
Animal Health	As for thin ashfalls (Table 1a)	Hudson (Wilson et al. 2011b): Puyehue-Cordón Caulle (Flueck 2013; Wilson et al. 2012b); Paricutin (Rees and Angeles 1970)	Tephra with moderate to high levels of available fluorine may cause acute or chronic fluorosis in grazing animals	Hekla (Thorarinsson and Sigvaldason 1971; Óskarsson 1980); Ruapehu Cronin et al. 1997, (998, 2003; Johnston et al. 2000); Longquimay (Araya et al. 1990); Laki (Gestsdóttir et al. 2006); Popocatepétl (Armienta et al. 2011)
	Rumen blockages leading to starvation and/or internal injuries		Risk higher for pregnant animals or animals in poor condition	
	Feed and water sources become smothered and inaccessible. Can also cause exposed feed to become unpalatable to animals causing malnutrition		Polioencephalomalacia in cattle and sheep due to excess sulphur (which tephra can introduce) being ingested. Symptoms include brain damage, blindness and muscle spasms	
	Tephra clogging on fleece		Tephra can also release aluminium that can prevent phosphorous absorption, but in small amounts can protect against fluorosis	
(C) Very thick ashfall (>500 mm)				
Soil	Fertile soil horizon completely buried and cut off from normal carbon, nitrogen, and oxygen cycles. Water infiltration prevented	Lanzarote (Diaz et al. 2005); Mt St Helens (Cook et al. 1981); Hudson (Wilson et al. 2011b); Puyehue-Cordón Caulle (Wilson et al.2012a, b); Ruapehu (Cronin et al. 1998; Johnston et al. 2000); Fuego and El Chichón (Varekamp et al. 1984; Veneklaas 1990); Others (Ayris and Delmelle 2012; Smith et al. 2010)	Loss of soil fertility as normal soil cycles cease.	Mt. St Helens (Dahlgren et al. 1999; Sneva et al. 1982); Kasatochi Island (Wang et al. 2010); Popocatepétl (Armienta et al. 2011) Others (Ayris and Delmelle 2012; Ugolini and Dahlgren 2002; Zheng 2010)
			Ash deposits typically have low organic content and cation exchange capacity which limits their fertility	Ayris and Delmelle (2012), Shoji et al. (1993)

Table 1 continued

	Physical impacts	Examples and references	Chemical impacts	Examples and references
Vegetation	Large amount of breakages due to tephra loading. Large clasts within the thick tephra fall strip and abrade vegetation	Merapi (Wilson et al. 2007); Mt. St Helens (Antos and Zobel 1985; Cook et al. 1981; Dale et al. 2005; Seymour et al. 1983; Sneva et al. 1982); Hudson (Wilson et al. 2011a, b); Puyehue-Cordón Caulle (Wilson et al.2012a, b)	As for moderate ashfalls (Table 1b)	Merapi (Wilson et al. 2007); Mt. St Helens (Cook et al. 1981; Sneva et al. 1982); Pinatubo (Mercado et al. 1996)
	Pasture completely smothered requiring resowing. Seedings and younger crops and plants covered. Horticultural crops fail due to burial, breakages, and abrasion	Hudson (Wilson et al. 2011b)	Could cause damage to root apex due to acidity and aluminium complexes	Smith et al. (2010); Zheng (2010)
Animal Health	As for moderate ashfalls (Table 1b)	Hekla (Thorarinsson and Sigvaldason 1971; Óskarsson 1980); Longquimay (Araya et al. 1990); Laki (Gestsdóttir et al. 2006)	As for moderate ashfalls (Table 1b)	Hekla (Thorarinsson and Sigvaldason 1971; Óskarsson 1980); Laki (Gestsdóttir et al. 2006)

In this study, we present and discuss post-event agricultural impact assessment data from three recent eruptions in Patagonia (Hudson 1991; Chaitén 2008; Cordón Caulle 2011). Impacts varied considerably with respect to both the depth of tephra fall and with vulnerability characteristics (VC) such as farm size, farm type, and access to resources such as machinery and irrigation. This enabled us to evaluate how both the hazard intensity measures (HIM) and the VC interacted to generate the impacts observed. These large magnitude, explosive, silicic eruptions each deposited tephra over >75,000 km^2 in the Patagonian region of South America, including large areas of productive agricultural land (Fig. 1; Table 3) (Buteler et al. 2011; Martin et al. 2009; Wilson et al. 2011a). Each eruption caused substantial impacts to agriculture in each tephra fall zone. However, impacts varied considerably depending on the load of tephra received (kg/m^2), whether tephra was remobilised by aeolian or fluvial processes, the characteristics of exposed farms, time of year, local climate conditions, and the role and resources of supporting agencies. Understanding how these factors influence impacts or damage will improve risk assessments, and was investigated by relating indices of tephra hazard intensity with

Table 2 Definitions of various risk and impact assessment terminology as they will be applied within this study

Term	Definition	References
Risk	The probability of an events negative consequences	UNISDR (2009)
Risk assessment	A methodology used to predict the probability of an events characteristics and the consequences, using a probabilistic hazard model and vulnerability assessment information	UNISDR (2009)
Impact	The effect a hazardous event has on an exposed system. Defined as a function of the hazard, and the vulnerability and exposure of a system (I = H V E)	Jenkins et al. (2014b)
Pre-event impact assessment	Prediction of the consequences of an event using hazard scenarios, vulnerability information, and exposure inventories, which does not have probabilities attached to it	
Post-event impact assessment	Assessment of the consequences of an event, and the hazard characteristics and vulnerabilities of exposed assets that influenced these	
Hazard	A phenomenon or event that poses a danger to life, property, economy, or social systems	UNISDR (2009)
Hazard intensity metrics (HIM)	The characteristics and properties of a hazard that can be measured and related to impacts	Wilson et al. (2014)
Exposure	People, property, and systems that are within hazard zones and subject to impacts	UNISDR (2009)
Exposed assets (EA)	Asset types within the hazard zone.	
Vulnerability	How susceptible to damage the effected systems are.	UNISDR (2009)
Vulnerability characteristics (VC)	The characteristics of a community, system, or assets that make it susceptible to the damaging effects of a hazard	UNISDR (2009)
Vulnerability Assessment	Methodology used to identify and/or quantify the vulnerability characteristics of an exposed system	

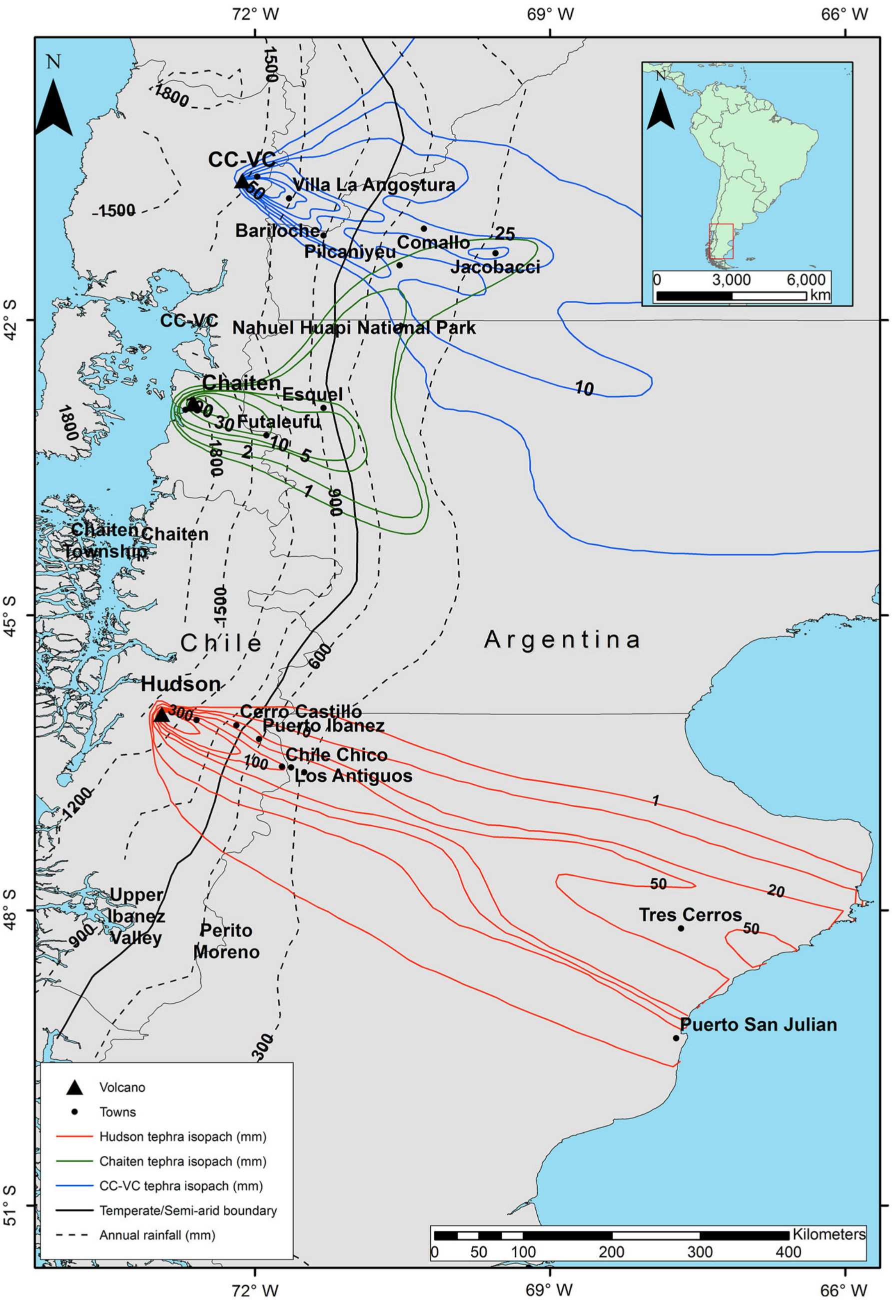

Fig. 1 Locations of the three study volcanoes and tephra thickness isopachs (from Scasso et al. 1994, Hudson; Watt et al. 2009, Chaitén; Wilson et al. 2012b, Cordón Caulle) across Chile and Argentina. Locations discussed in text and annual rainfall isohyets (in mm) (FAO 2001). The approximate limit between the semi-arid and temperate regions is also shown

Table 3 Study site information (Smithsonian 2014)

	Hudson	Chaiten	CC-VC
Location	45.9°S, 72.97°W	42.83°S, 72.65°W	40.59°S, 72.12°W
Elevation (m)	1905	1122	2236
Volcano type	Stratovolcano	Caldera	Stratovolcano/fissure
Start date	08-Aug-91	02-May-08	04-Jun-11
End date	27-Oct-91	31-May-11	21-Apr-12
VEI	4–5	4	3
Magmatic composition	Dacitic	Rhyolitic	Dacitic-Rhyolitic
Max. plume height (km)	18	15	13
Tephra fallout area (km2)	100 000	100 000	75 000
Year of last prior eruption (VEI)	1971 (3)	1642 (4)	1990 (1)
Previous eruptions	12 holocene eruptions. The largest was caldera forming 6700 years BP	Major caldera forming eruption 9400 years BP. Last prior eruption in 1640 (VEI 4)	Eruption in 1960 (VEI 3) deposited tephra over a similar area to the 2011 event
Time of visit	Jan–Feb 2008	Jan–Feb 2009 and Mar 2012	Feb–Mar 2012
Time between eruption and field work	16 years, 5 months	9 months and 3 years, 10 months	9 months

measures of vulnerability for exposed farms. This paper presents a brief review of previous tephra impact and risk assessments for agriculture (Sect. 2), followed by the presentation of impact, hazard, and vulnerability information across the three volcanic disasters and the emergency management strategies employed (Sect. 4). This information is used to inform a system of classifying impacts into a performance-based damage state scale (Sect. 5). The influence of tephra fall and exposed asset vulnerability characteristics on agricultural impacts and how these will influence response and long-term recovery are discussed. Finally, considerations for future post-event tephra impact data collection for agriculture are discussed (Sect. 6).

2 Impact assessments

2.1 Overview of impact assessments for natural hazard events

Impact and risk assessments both aim to quantify and predict the consequences of a hazard event, by considering hazard, exposure, and vulnerability characteristics (Smith 2013) (Fig. 2). The distinction is that impact assessments do not have probabilities attached to the different outcomes that could occur. Both types of assessments can be undertaken either before or after a hazardous event and use deterministic or probabilistic approaches (definitions in Table 2). Vulnerability assessments account for how the specific characteristics of a system influence impacts that will occur under different hazard intensities (Fuchs et al. 2012).

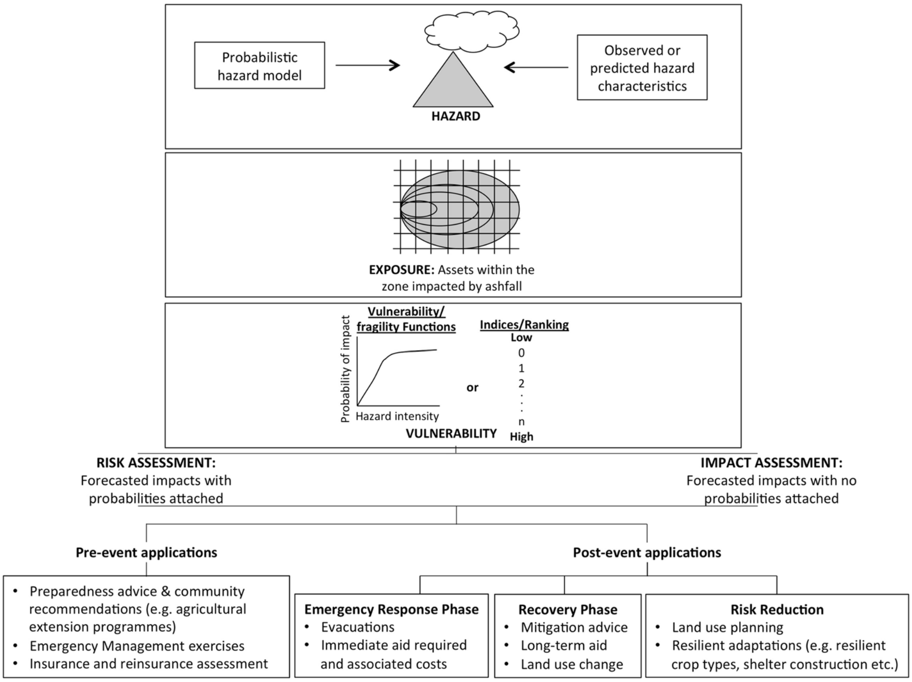

Fig. 2 Impact and risk assessment relationships and their associated inputs and outputs

2.1.1 *Purpose of impact assessments*

The main objectives of impact assessments are providing information to emergency managers to coordinate and plan response post-event, to identify areas pre-event that will need evacuating, and help to aid distribution planning (Alexander 2002) (Fig. 2). The insurance industry also uses pre- and post-impact assessments to refine more sophisticated risk modelling and also uses past damage costs from impact assessments to examine future event estimates (Friedman 1984; Mileti and Henry 1999). Post-EIA play a vital role in providing the qualitative and quantitative data for vulnerability and risk assessments, and in strengthening the understanding of possible hazard scenarios and the vulnerability characteristics of an area and their influence on loss. Pre-EIA provide predictive capacity where there are insufficient empirical and/or analytical data to accurately constrain the probabilities of outcomes, meaning that a full risk assessment is not possible. These are particularly important when assessing social or economic vulnerability, as unlike with physical vulnerability, these cannot be investigated using laboratory or engineering approaches. Inputs and outputs of previous impact and risk assessments are summarised in Fig. 2.

2.1.2 *Recording impact assessment information*

Impact can be recorded in a range of ways which may include physical, economic, or social losses and direct or indirect damage after a range of hazard scenarios (Smith 2013). Post-event assessment of damage to buildings and infrastructure is commonly undertaken in a range of disciplines, with earthquake engineering exhibiting the most well-documented methods, with assessment undertaken at various scales from response-based field work, which assesses damage to individual structures (Bazzurro and Cornell 2004; Erdik et al. 2011; Ghobarah 1999; Rossetto et al. 2014), to remote sensing (Brunner et al. 2010; Chiroiu and Andre 2001). The core objective of post-EIA is to assess the hazard intensity in space and time, what elements were exposed, the element's vulnerability characteristics, and observed impacts (Fig. 2). However, how the vulnerability of exposed assets influences the impacts appears to be consistently less comprehensively recorded than the effect of different hazard characteristics and intensities, particularly for volcanic hazard risk (Jenkins et al. 2014a). This imbalance has been identified by various authors (e.g. Sparks et al. 2013; Wilson et al. 2014) and needs addressing to improve the value and utility of future impact and risk assessments (both pre- and post-event) and ultimately to improve disaster risk management.

2.1.3 Relating hazard intensity metrics to impact information

Simplistic impact assessments are essentially exposure assessments, which relate hazard intensities (such as ground acceleration for earthquakes, or tephra thickness after a volcanic eruption) and exposed assets, in order to define what area is affected. Whilst this is a good rapid approach, the severity of impacts is not presented, which limits planning specific management strategies. Assessments can be improved by relating the hazard intensity to an estimated level of impact, depending on the vulnerability of the exposed system. Three main approaches have been used to relate hazard, exposure, and vulnerability data to observed impacts:

1. Damage thresholds that estimate certain impacts which are likely to occur when certain hazard intensities are exceeded (e.g. Wilson et al. 2014);
2. Damage states provide a measure of common states of damage caused by the natural hazard and exposed element. They typically offer greater explanation than damage thresholds and may be presented over a range of hazard intensities;
3. Fragility functions are equations which express the probability of differing levels of damage sustained for different elements as a function of chosen hazard intensity measure (Baker 2014)

Both damage threshold and damage state approaches are a way of standardising qualitative impact information within a quantitative scale with impact descriptors, in order to allow for comparisons and trends to be easily identified (Krausmann and Mushtaq 2008). Damage state and fragility function approaches have found favour because they allow for some forecasting of impacts to be undertaken with little hazard metric input. Whilst there are some limitations with applying a standardised index, they allow for damage across different areas that can be compared within a framework. In some instances, damage states have been connected with hazard intensity thresholds such as exceedance of a particular ground acceleration (Kircher and Nassar 1997), dynamic pressure within a pyroclastic density current (Spence et al. 2004), or the load of a tephra deposit (Jenkins et al. 2014a). These must be matched against the impacted element type (e.g. infrastructure sector, type of agriculture) and specific site characteristics and assume that similar systems will mostly perform similarly under common hazard intensities. Variability of impacts can be taken into account by adding uncertainty bounds. Where limited vulnerability data are available, broad homogenous element classes must be used which can reduce the applicability and resolution of the product of an impact or risk assessment. Connecting damage scales with more quantitative information about economic costs and vulnerability information is an ongoing area of research (Blong 2003; Spence et al. 2005) and will allow for the refinement of impact assessment data.

Fragility functions are widely used in natural hazard impact and risk assessment, particularly in earthquake engineering (Rossetto et al. 2013, 2014). There is strong desire to develop a similar set of resources for volcanic hazards, such as tephra fall, to allow for more accurate modelling and forecasting of loss (Wilson et al. 2012a; Jenkins et al. 2014b).

2.2 Agricultural impact assessment after tephra fall

Numerous agricultural impact assessment studies both before and after tephra fall events have been undertaken (Supp. Mat. 1). Post-EIA have focussed primarily on local-scale, observational data collected from fieldwork and interviews with farmers and agricultural agencies, and more quantitative information on economic losses at a regional scale (Cronin et al. 1998; Wilson et al. 2007, 2011a). Observational case studies after a tephra fall event have provided valuable data towards vulnerability analysis, complimented by some laboratory trials exploring specific aspects of HIM and VC (Wilson et al. 2014). Consistent methodologies of tephra impact assessments of agriculture have been developed over the past 15 years allowing broad trends in what HIM and VC influenced impacts to be identified (Supp. Mat. 1), but no clear, widely applied guidelines exist (Wilson et al. 2014).

When considering tephra fall on agricultural systems, post-EIA for agriculture (Supp. Mat. 1; in particular Wilson et al. 2011a) have identified that the type and severity of

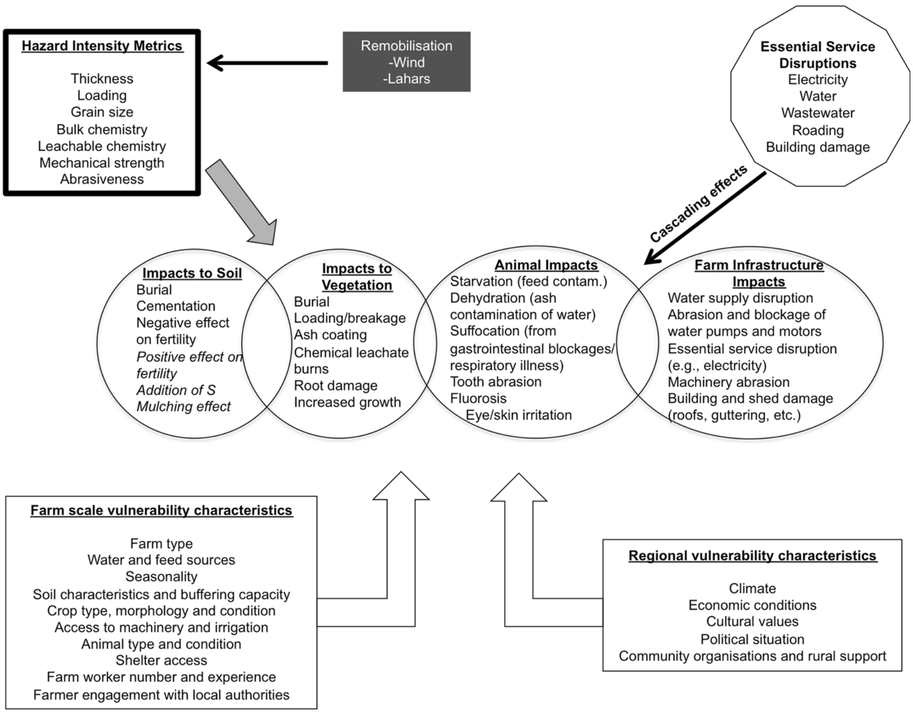

Fig. 3 Relationship between tephra impacts to soil, vegetation and animals, hazard intensity measures, and regional and farm-scale vulnerability characteristics

impacts are dependent on: (1) the characteristics and intensity of the hazard experienced at a particular site (HIM), such as the tephra loading (i.e. kg/m^2), deposit thickness, grain size, soluble chemistry, mechanical strength: broadly termed hazard intensity metrics, and (2) the characteristics of the exposed agricultural system(s) at that particular site (VC), such as the type of farm, production intensity, reliance on inputs (e.g. water, electricity, etc.), labour resources: called vulnerability characteristics. Additionally, impacts to other societal elements can cause cascading impacts to agricultural systems, such as loss of power preventing use of water pumps, road closures can hinder evacuation and the transport of supplies (Wilson et al. 2014). This interdependency highlights the value of holistic assessments which consider infrastructure and primary industry impacts (Sword-Daniels et al. 2014; Wilson et al. 2012a, b). The range of influential HIM, VC, and associated agricultural impacts is summarised in Fig. 3.

The most recently developed, globally applicable damage state estimates for agricultural impacts due to tephra fall were developed as part of the Global Assessment Report 2015 (GAR-15) on Disaster Risk Reduction for the United Nations-International Strategy for Disaster Reduction (UN-ISDR) (Jenkins et al. 2014b). Tephra thicknesses commonly observed at each damage state were then assigned to each sector, based primarily on expert judgement. Whilst this is a useful pre-EIA tool that can be generally applied to a range of events, Jenkins et al. (2014b) acknowledge it does not take into account the influence that other HIM and VC unique to a particular agricultural system could have on the thickness thresholds for each damage state.

Agricultural fragility functions have been created for pastoral agriculture, horticulture and forestry for the New Zealand setting by Wilson and Kaye (2007). These curves estimate first-order economic losses to farms, separating losses into production and asset bases. In this case, most of the curve fitting was based on expert judgement rather than empirical data, and few VC (additional to seasonal effects) were included.

3 Methods

Data for this study was primarily collected during impact assessment study visits in areas exposed to tephra fall after the three eruptions (summarised in Table 3). Agricultural areas were visited along a transect of the tephra fall zones approximately parallel to the main tephra fall out axis where possible. Tephra thicknesses were recorded from published tephra thickness isopach maps (Scasso et al. 1994, Hudson; Watt et al. 2009, Chaitén; Wilson et al. 2012b, Cordón Caulle) and farmer estimates. There are some uncertainties associated with these measurements (such as compaction and remobilisation of the deposit before measurements can be taken) that need to be taken into account. Semi-structured interviews were undertaken with farmers as well as additional meetings with production managers and agricultural agency staff in major centres and agricultural service towns. Interview methodology was reviewed and approved by the University of Canterbury (Christchurch, New Zealand) Human Ethics Committee prior to each trip. These were undertaken at varying times after the initial event (Table 3). These timings were chosen in order to allow time for the impacts to mature [in the case of Chaitén and Cordón Caulle-volcanic complex (CC-VC)] or to assess long-term recovery (Hudson). The methods used are described in Wilson et al. (2011a, b) (for Hudson) and Wilson et al. (2012b) (for CC-VC). The same methods were applied after the Chaitén eruption.

Interview data were compiled into tables, and common themes identified. The relationship between animal deaths and production losses, and the observed impacts were investigated to assess the farm impacts that occurred in order to cause significant production losses. In order to quantify this observational impact data, damage states were developed using performance-based indicators. This involved assessing production changes and the different needs farms developed after the tephra fall (i.e. reliance of supplementary feed/aid) and then ascertaining the corresponding level of damage sustained for each of these groups of different production change scenarios. 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.

Data collected during interviews were also collated in order to assess the relationships between HIM, VC, and agricultural impacts. Production change or animal deaths were compared to various hazard and vulnerability data that were collected in interviews in order to identify trends. This was undertaken to try and identify causal mechanisms for loss, which can then be used as a tool to both predict losses from future events, particularly with VC which can be assessed pre-eruption, and predict ongoing losses over the weeks and months after the initial tephra fall and impact assessment.

4 Agricultural setting and impact observations

In order to fully assess the VC of affected farms, the regional setting and environment need to be well understood, as aspects such as climate, soil type, and ecosystems could potentially influence the impacts received. The study area covered a transect running from the temperate Andean environment of Chile out east to the semi-arid Argentine steppe. Precipitation levels in the region vary widely with the annual rainfall on the western coast of Chile exceeding 2000 mm, but on the opposite coast of Argentina levels only reach <200 mm per year (Fig. 1). This difference is caused by the rain shadow effect, where a predominant westerly flow of air hits the Andes and causes a hyper-humid environment to form; conversely, on the downslope side, only dry air arrives forming a semi-arid environment. This environmental difference also influences the soil types seen across the impacted areas. The dominant soil types in the study area are illustrated using the Food and Agriculture Organisation classification scheme (FAO 1997) (Supp. Mat. 2).

The soils in the study area generally become less fertile towards the east (from fertile Andisols and Cambisols in the temperate zone, to Yermisols in the semi-arid region), which in conjunction with less precipitation restricts the type and intensity of farming that can occur (Salazar et al. 1982). Areas in the temperate Andean zone have the capacity for high-intensity farming, horticultural activities, and cattle farming, whereas farms in the semi-arid steppe are more suited to relatively low-intensity, sheep and goat farming where irrigation is not available (i.e. usually stocking rates of less than 1.5 animals/hectare) (Aruani and Sánchez 2003). These environmental differences create two distinct zones of farming: the temperate zone and the semi-arid region.

Tephra fall affected a variety of land use types across a wide area (Fig. 4, Supp. Mat. 3). At tephra thicknesses of >100 mm, the majority of land affected is classified as 'Forest—with agricultural activities' (i.e. the Nahuel Huapi National Park agricultural area), with a considerable amount of 'urban area' (20 %) also receiving 150–300 mm. At less than 100 mm, the majority of tephra covered land is either 'shrubs—low livestock density' or

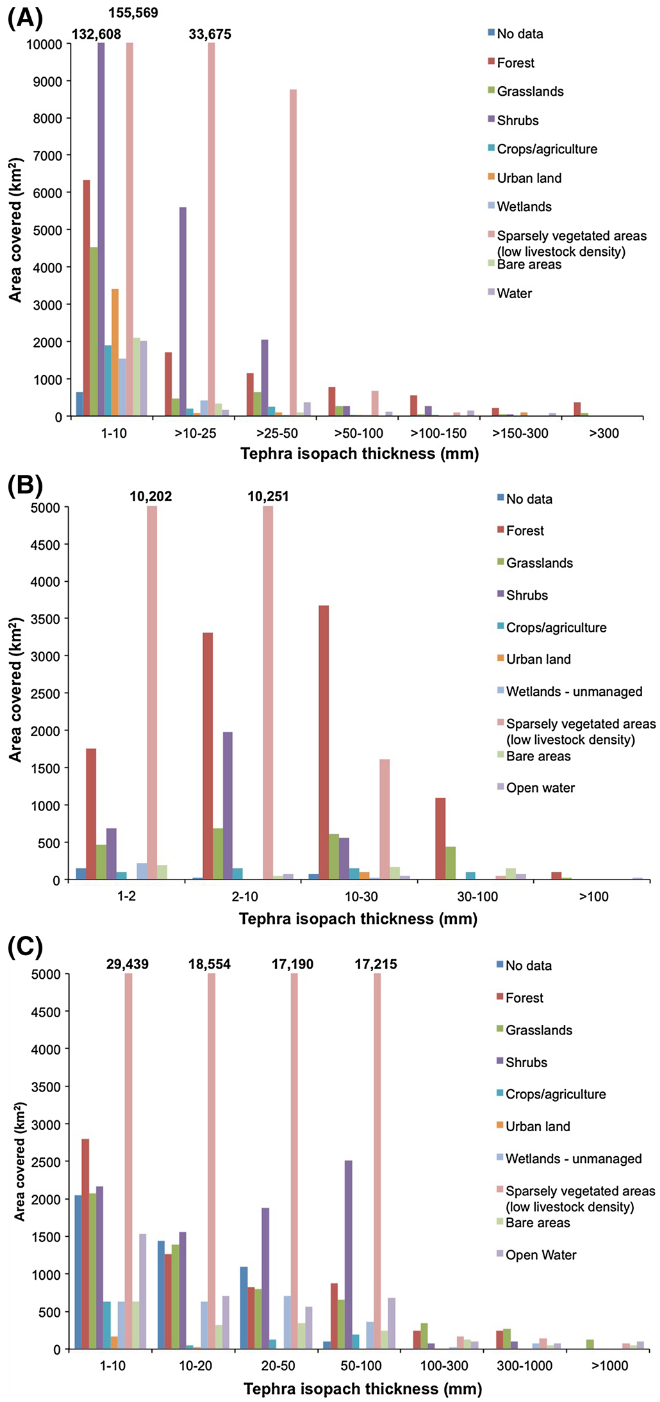

Fig. 4 Area of land use types (FAO 2008) covered by tephra isopachs after each eruption for **a** Hudson; **b** Chaiten; and **c** CC-VC. See Supp. Mat. 3, 4, and 5 for raw data

'sparsely vegetated areas—with low livestock density', which represents the semi-arid, steppe farming region (Fig. 4, Supp. Mat. 3; FAO 2008).

The agricultural impact data presented were collected during interviews and field visits after the three tephra fall events and are summarised in Table 4.

4.1 1991 Hudson eruption

The 1991 Hudson eruption primarily deposited tephra across the Aísen Province of Chile and the Santa Cruz Province of Argentina (Fig. 1). Tephra was deposited over 100,000 km^2, with thicknesses of over 1000 mm recorded in proximal areas (Table 3). Farming in the area is dominantly pastoral farming of cattle in the west and sheep on the eastern steppe, with horticulture concentrated in the valleys around Chile Chico and Cerro Castillo (Table 4). A full summary of the farms interviewed and information collected is presented in Supp. Mat. 4.

4.1.1 Pastoral impacts

Overall, an estimated 1 million animals died due to the tephra fall preventing normal grazing (Wilson et al. 2011a). This was due primarily to starvation and gastrointestinal blockages caused by tephra-contaminated feed.

The major cause of agricultural loss in areas that experienced <150 mm of tephra fall was extensive, prolonged wind remobilisation of tephra deposits. Effects on livestock and vegetation due to wind remobilisation of tephra deposits were similar to those experienced with initial tephra falls, however, occurred for much longer timeframes (Wilson et al. 2011a). At the time interviews were undertaken (over 16 years after the initial eruption), areas such as Puerto Ibanez (Chile) were still experiencing active wind remobilisation of tephra deposits, despite some effort to stabilise deposits and protect vegetation (re-vegetation, irrigation, wind breaks). This led to farm abandonments both immediately after the tephra fall and in the months afterwards as conditions persisted. Tephra stabilisation methods were based on experience with wind remobilisation after the 1980 Mt St Helens eruption, where cultivation or tilling tephra into the soil, revegetation of deposits, and tephra removal and capping were all employed (Collins and Dunne 1986; Fowler and Lopushinsky 1986). Farms that immediately attempted cultivation or deposit stabilisation were more able to withstand the wind remobilisation of tephra deposits over the months and years after the eruption (Wilson et al. 2011b).

The eruption occurred at the end of the winter before spring pasture growth could replenish pasture and improve waning animal condition. This timing also meant that the tephra fall occurred at the start of the drier period (winters generally drier than summers; FAO 2001), leaving the area vulnerable to remobilisation. Some farmers also reported tephra cementing and forming a barrier between the soil and the environment, preventing the infiltration of water into the soil and pasture.

The risk of fluorosis occurring in livestock due to tephra ingestion and contamination of feed and water supplies was a major concern for farmers after the eruption. Tephra leachates can sometimes contain levels of fluoride that are toxic to livestock (Witham et al. 2005), such as after the 1970 Hekla eruption where thousands of sheep died due to acute fluorosis (Thorarinsson and Sigvaldason 1971). The potential of the Hudson tephra to cause fluorosis was specifically considered and excluded as a loss mechanism (Rubin et al. 1994).

Table 4 Summary of the agricultural impacts across the three eruptions (recorded at the time of maximum impact due to tephra fall)

Event	Year	Affected area			Climate zone	Main agriculture types	Species	Tephra thicknesses (mm)	Prolonged wind remobilisation (months–years)	Animal health effects	
		Country	Province	Locality						Starvation	Blindness due to eye abrasion
Hudson^	1991	Chile	Aisen	Ibanez Valley	Temperate	Pastoral	Sheep, cattle	1500		✔	
				Puerto Ibanez	Temperate	Pastoral	Sheep, cattle	250		✔	
				Cerro Castillo	Temperate	Pastoral, horticultural	Sheep, tomatoes, cherries, potatoes	100	✔	✔	
				Chile Chico	Semi-arid	Pastoral, horticultural	Sheep, tomatoes, cherries, potatoes	100	✔	✔	✔
		Argentina	Santa Cruz	Los Antiguos	Semi-arid	Pastoral, horticultural	Sheep, tomatoes, cherries, potatoes	80	✔	✔	✔
				Perito Moreno	Semi-arid	Pastoral	Sheep	40	✔	✔	✔
				Tres Cerros	Semi-arid	Pastoral	Sheep	40	✔	✔	
Chaiten	2008	Chile	Los Lagos	Chaiten	Temperate	Pastoral, forestry	Cattle, sheep	350		✔	
				Futaleufu	Temperate	Pastoral	Cattle, sheep	150		✔	
		Argentina	Chubut	Esquel	Transitional	Pastoral	Sheep	5	✔	✔	✔
			Rio Negro	Pilcaniyeu	Semi-arid	Pastoral	Sheep, goats	1	✔	✔	
CC-VC	2011	Argentina	Neuquen	Nahuel Huapi National Park	Temperate	Pastoral	Cattle, deer, horses	350		✔	
		Argentina	Rio Negro	Jacobacci/Comallo	Semi-arid	Pastoral	Sheep, goats	50	✔	✔	✔

Table 4 continued

Event	Year	Affected area			Animal health effects		Livestock autopsy findings (where undertaken)	Primary cause of livestock deaths	Evidence of fluorosis	Vegetation issues	Approximate production losses >50 %
		Country	Province	Locality	Tooth abrasion	Immobilisation of sheep due to tephra weight in fleeces					
Hudson^	1991	Chile	Aisen	Ibanez Valley	✔		Tephra blockages in rumen and gastrointestinal tracts	Immobilisation due to tephra fall, gastrointestinal blockages, starvation, dehydration		Complete burial	✔
				Puerto Ibanez	✔	✔	Asphyxiation due to intestinal blockage pressing on lungs	Immobilisation due to tephra fall, gastrointestinal blockages, starvation, dehydration		Burial, breakages	✔
				Cerro Castillo	✔		Tephra blockages in rumen and gastrointestinal tracts	Gastrointestinal blockages, eye irritation, tooth abrasion		Wind abrasion, vegetation shearing	
				Chile Chico	✔	✔	Tephra blockages in rumen and gastrointestinal tracts	Gastrointestinal blockages, eye irritation, tooth abrasion		Wind abrasion, vegetation shearing	
		Argentina	Santa Cruz	Los Antiguos	✔	✔	Asphyxiation due to intestinal blockage pressing on lungs	Gastrointestinal blockages, eye irritation, tooth abrasion		Wind abrasion, vegetation shearing	
				Perito Moreno	✔			Gastrointestinal blockages, eye irritation, tooth abrasion		Wind abrasion, vegetation shearing	✔
				Tres Cerros	✔			Gastrointestinal blockages, eye irritation, tooth abrasion		Wind abrasion, vegetation shearing	✔

Table 4 continued

Event	Year	Affected area			Animal health effects		Livestock autopsy findings (where undertaken)	Primary cause of livestock deaths	Evidence of fluorosis	Vegetation issues	Approximate production losses >50 %
		Country	Province	Locality	Tooth abrasion	Immobilisation of sheep due to tephra weight in fleeces					
Chaiten	2008	Chile	Los Lagos	Chaiten	✔		Hard lumps of tephra completely blocking rumen	Starvation		Burial, breakages	✔
				Futaleufu	✔		Hard lumps of tephra completely blocking rumen	Starvation		Burial, breakages	✔
		Argentina	Chubut	Esquel	✔			Tooth abrasion, gastrointestinal blockages		Wind abrasion, vegetation shearing	
			Rio Negro	Pilcaniyeu	✔			Tooth abrasion, loss of condition		Wind abrasion, vegetation shearing	
CC-VC	2011	Argentina	Neuquen	Nahuel Huapi National Park	✔			Starvation, gastrointestinal blockages	Possible chronic risk	Burial, breakages	
		Argentina	Rio Negro	Jacobacci/ Comallo	✔		Hard lumps of tephra completely blocking rumen	Tooth abrasion, loss of condition	Possible chronic risk	Wind abrasion, vegetation shearing	✔

* Farming takes place within the national park where farmers lease a portion of the national park; however, boundaries are not strictly adhered to

^ Summary from Wilson et al. (2011a)

4.1.2 Horticultural impacts

Horticulture in the affected area (commonly cherry orchids, tree fruits, and root vegetables) typically experienced the loss of between one and three harvests, due to tephra fall and compounded by the continued wind remobilisation. This caused abrasion and acid damage to flowers and leaves. Fortunately, the time of year that the tephra fall occurred was more favourable for horticulture than it was for pastoral farming, as flowering had not yet occurred (Wilson et al. 2009). However, this relief was short lived as wind remobilisation of tephra deposits in the Puerto Ibáñez, Chile Chico, and Los Antiguos regions continued for many years after the eruption, damaging flowers and fruit. Many horticulture farmers resorted to the use of greenhouses or shelter belts for six years after the eruption (Wilson et al. 2011b).

4.2 2008 Chaitén eruption

Tephra from the 2008 Chaitén eruption was deposited across the temperate cattle farming in the Los Lagos Province of Chile, and the semi-arid, sheep and goat farming of the Chubut and Río Negro provinces of Argentina. Interviews were undertaken across this region (Supp. Mat. 5).

4.2.1 Pastoral impacts

Pasture in the Chaitén and Futaleufú areas was buried by up to 350-mm tephra leaving it inaccessible to livestock. This led to animals becoming malnourished and without evacuations or substantial supplementary feed succumbing to starvation. Due to dry conditions prior to the eruption, pasture was already not in optimal condition leading to further losses. The eruption resulted in the death of 25,000 animals, predominantly cattle (Assoiaćion Gremial de Productores de Leche de Osorno 2014).

In the temperate, Andean region (Chaitén and Futaleufú), following the tephra deposition, a period of heavy snow and rainfall hit the proximal region. This became an issue when in some areas, the wet snow froze cementing the tephra fall, further increasing reliance on supplementary feed for animals. Despite wetter conditions aiding tephra incorporation, thicknesses of over 200 mm meant that there was still a shortage of available grazing land, causing farmers in the area to evacuate or sell livestock. As has been seen after previous events, such as 1999 Tungurahua (Ecuador) (Leonard et al. 2005), 1991 Pinatubo (Philippines) (Mercado et al. 1996), and 1943–1956 Paricutin (Mexico) eruptions (Eggler 1963), farmers forced to sell after tephra fall (due to lack of available feed and declining animal condition) received much lower prices for livestock than those pre-eruption. In the steppe region, pasture quality continued to decline in the months after the eruption due to dry summer conditions and wind remobilisation of tephra deposits. As with the 1991 Hudson eruption, the climatic zone and wind remobilisation occurrence created a divide in impacts, where in the semi-arid steppe losses continued and recovery did not commence for many months after the eruption. Whilst wind remobilisation of tephra deposits was less severe in intensity, area, and duration than what was experienced after Hudson, as rainfall was greater and wind speeds lower (Fig. 5), this still led to a high reliance on supplementary feed throughout the affected area and animal losses of up to 10 % in an area (Pilcaniyeu) that only received 3–5 mm of initial tephra fall. Additionally, many farmers were concerned about the toxicity of the tephra fall when ingested by animals. Whilst tephra leachate analysis showed that the risk of chemical toxicity in

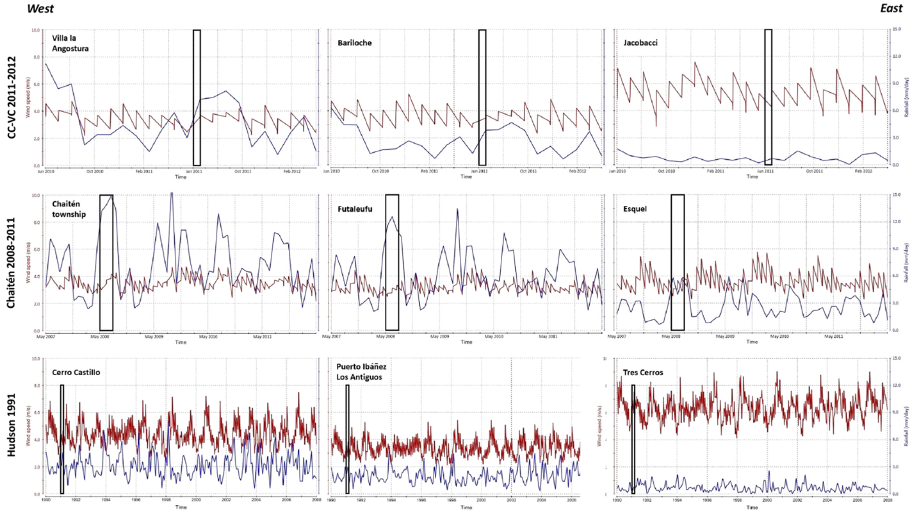

Fig. 5 Daily rainfall and surface wind speeds from monthly averaged ERA-Interim reanalysis records. For each volcano (*row*), reanalysis data are shown for a time series from one year before the eruption until the time of our visit. *Upper red lines* are wind speed; *lower blue lines* are rainfall values; *black bars* show the main tephra producing stages of each eruption

livestock was very low (Durant et al. 2011), some farmers chose to sell livestock based on these fears.

4.2.2 Horticultural impacts

Horticultural and arable farming was observed in both the temperate and transitional zones, and in isolated areas in the steppe that had access to irrigation water. In the transitional zone where the temperate and semi-arid zones meet, tomato and other fruit and vegetable crops were grown under makeshift shelters or greenhouses. These farms had some losses due to vegetation burial and abrasion of leaves and fruit, but were able to recover relatively rapidly (within one harvest). This rapid recovery was due to greenhouses providing protection from ongoing wind remobilisation of tephra deposits and the accessibility of equipment for irrigation and tephra removal or cultivation.

Arable farms (dominantly wheat and maize) located in the temperate and transitional regions to the east of the volcano were also affected by tephra fall (40- to 50-mm tephra thickness). The eruption occurred when crops were in juvenile stages before spring growth, leaving plants vulnerable to structural damage and burial. However, crops experienced few losses and even reported increased yields of corn and wheat 3 years after the initial eruption. These increased yields were likely a consequence of the 'mulching' effect that the tephra provided, where it prevented the loss of soil moisture, and also possibly due to the addition of beneficial elements such as sulphur (Durant et al. 2011).

4.3 2011 Cordón Caulle (CC-VC) eruption

As with the two other Patagonia eruptions, interviews were undertaken across both the temperate zone predominantly in Chile and the semi-arid, Argentine steppe (Supp. Mat. 6).

Both environmental zones received tephra fall of greater than 50 mm in places and rely on agriculture as a major employer and contributor to the local economy.

4.3.1 Pastoral impacts

Studies undertaken in the Jacobacci (semi-arid steppe) area by local agricultural agencies after the eruption identified that animals would have been unable to access pasture through thick tephra deposits (Siffredi and Ayesa 2011). Estimates of the proportion of pasture becoming inaccessible due to tephra coverage ranged from 70 to 80 %, for very wet valleys, up to 90–100 % for drier mallines (Siffredi and Ayesa 2011). This led to widespread cases of starvation, where farmers observed a progressive loss of animal condition resulting in death (Juan Escobar, Municipalidad de Ingeniero Jacobacci 2012). In the Nahuel Huapi National Park, any pastoral species were buried by over 300 mm of tephra. This meant that animals relied on taller forage such as shrubs, or supplementary feed.

As with the previous two case studies, there was a clear difference in impacts between the temperate, Andean zone and the semi-arid, Argentine steppe, with lower rainfall and higher wind speeds in the steppe (Fig. 5) increasing wind remobilisation occurrence. In the steppe area, municipality staff estimated that livestock losses after the tephra fall were around 40–60 % for a total regional herd of 225,000 sheep and 60,000 goats. The losses in the temperate, Nahuel Huapi National Park were much lower despite the closer proximity to the volcano and greater tephra fall depth (Table 4) and were comparable to those experienced after a severe winter (around 21 %) (Marcos Arretche, Proteccion Civil Municipalidad Villa la Angostura, pers. comm. 2012). Many farmers in the national park slaughtered a small number of animals for their households and sold animals before their condition worsened.

As with the Hudson eruption, farmers immediately were concerned with the potential for toxicity to livestock due to ingestion of tephra. In particular, the possibility of acute fluoride toxicity was a concern and was a target of leachate studies. Several studies have reported severe dental and skeletal fluorosis in wild deer populations in the depositional area of the eruption (Flueck and Smith-Flueck 2013a, b) and an increase in post-eruption rates of accumulation of fluoride (F) in bones of sheep on farms in the depositional area (Flueck 2013). The levels of F accumulation in bones are considered by the author of the latter study to be highly likely to cause chronic fluorosis. Whilst the F levels were not high enough to cause acute toxicity, the elevation of F over the long term will likely have negative health consequences for livestock such as bone and tooth lesions and malformations (Livesey and Payne 2011). However, levels were too low to accumulate in livestock rapidly enough to cause acute fluorosis (Craig et al. *in prep*), where death will likely occur in a matter of days due to cardiac arrest and metabolic inhibition (Cronin et al. 2000).

4.3.2 Horticultural impacts

The affected area contained very little horticulture due to the already challenging farming conditions in the steppe region and forest cover in the national park. A cabbage farm in the transitional region between semi-arid and temperate was reported abandoned due to the ongoing impacts from wind remobilisation of tephra.

Horticulture, mainly consisting of fruit trees such as apple and pear, around the town of San Martin de los Andes was also affected (Graziano and Miserendino 2011). Fruit suffered abrasion and was damage due to remobilised tephra fall, and yields the season immediately after the tephra fall were low. However, the majority of farms recovered to near pre-eruption levels by the next years harvest.

4.4 Overall themes

Overall, across the three events the major agricultural impacts from tephra fall and wind remobilisation of tephra deposits identified are summarised in Table 4. Contamination of clean feed and water supplies for livestock, livestock evacuation, and applying protection to crops to avoid burial and damage or contamination by the tephra fall were the major impacts and response actions. Four main factors that influence the type and severity of impacts were identified from common themes within the transcribed interviews (Table 5). These were: (1) tephra deposit thickness; (2) climatic region and amount of precipitation prior to and immediately after tephra fall; (3) time of year the tephra fall occurred; and (4) farm 'improvement' assets (e.g. shelter, greenhouses, and machinery for cultivation and irrigation).

4.4.1 Emergency management strategies

A further finding from the three volcanic disasters is the role of risk management strategies (pre- and post-tephra fall) in reducing impacts. Whilst this may not be overly surprising, identifying the effectiveness of risk management strategies is an important contribution to global volcanic disaster risk management (Smith 2013). Effective emergency management that will lead to disaster risk reduction (DRR) can be separated into five main principles: pre-event mitigation and preparedness; warning/communication of event occurrence; the initial response; and post-event recovery (Haddow et al. 2013). These stages and the observed strategies across the three case studies are presented in Table 6.

4.4.2 Pre-event mitigation and preparedness

In order to effectively undertake DRR, long-term mitigation and preparedness strategies need to be put in place prior to an emergency event (Alexander 2002) (Table 6). Few preparedness strategies were in place on Chilean or Argentine farms prior to the Patagonian eruption events, due to the low risk perception associated with tephra fall. However, one resilience building strategy was highly beneficial. During the 1990s and 2000s (prior to the Chaitén and CC-VC events), agricultural extension agencies supported development of farm improvement assets to support diversification and intensification of agricultural production in the affected areas, which reportedly reduced production losses (particularly in the Chaitén and Futaleufú areas, see Supp. Mat. 5) from tephra fall (Table 6). However, volcanic hazard-specific preparedness planning could be improved upon through planning exercises and review of emergency management strategies (Table 6).

4.4.3 Warnings

Prior to, or immediately after an eruption has occurred, a timely, widely disseminated warning, which contains accurate and applicable information, is an important part of effective volcanic emergency management (De la Cruz-Reyna and Tilling 2008). Interviews with farmers and agricultural agencies suggested farms proximal to the volcanoes (within ~20 km) were both well informed and managed by responding agencies or

Table 5 Table showing important HIM and VC identified through compiling factors that were identified as influencing agricultural impacts

Scale	HIM		VC	
	Pastoral	Horticultural	Pastoral	Horticultural
Farm			*Access to machinery* Farms able to remove or cultivate tephra recovered more rapidly	
	Thickness All case studies reported greater agricultural losses in areas with greater thicknesses. Thickness and loading determined the amount of pasture available and the amount of damage to horticultural crops		*Seasonality* Tephra falls during breeding season (pastoral) or seeding and flowering (horticultural) are more likely to cause damage *Farmer awareness* Lower losses in areas where farmers were aware of tephra impacts and/or had experienced them before	
	Grain size Contributes to animal ingestion, adherence to crops, and also to its remobilisation potential		*Systems failures* Agricultural losses exacerbated if other interdependent services disrupted such as electricity, roading, communications	
	Leachable chemistry of tephra Acid burns on pasture and horticultural crops. Risk of fluorosis in livestock		*Feed and water access* Clean feed and water, and access to supplementary feed determined animal mortality	*Type of crop* Crops such as rice, potatoes, and onions performed better after tephra fall than chillies, tomatoes, and tobacco
			Animal shelter and feed storage Protected animals from tephra ingestion, as long as tephra loading does not affect the structure	*Greenhouses* Use of greenhouses protects crop from tephra fall, as long as loading does not effect the structure
			Pre-existing animal condition Pregnant or malnourished animals more likely to die from starvation, dehydration, and fluorosis	
Regional	*Abrasiveness of tephra* Caused livestock tooth abrasion (pastoral), vegetation shearing and abrasion (horticultural), and damage to machinery		*Climate* Low rainfall led to wind remobilisation, and high rainfall caused lahars	
	Remobilisation potential The thickness, grain size, and location of tephra deposits will influence the spatial and temporal extent of any remobilisation		*Access to aid* The amount of aid (goods, services, and monetary assistance) available to each region	

Table 6 Management strategies across regions affected by the three eruptions, and changing damage states during recovery

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson 1991 Chile Aisen	Hudson 1991 Argentina Santa Cruz	Chaiten 2008 Chile Los Lagos
Pre-event								
1. Pre-event mitigation	Prolonged actions taken during 'non-emergency' time to reduce risks to people and property from future hazards	Broadly speaking mitigation actions include land use planning, retrospectively adapting assets to more resilient designs, and hazard-resistant construction and system design. For agricultural systems, this includes farming resilient crops/animals, abandoning the most at-risk land, having shelter available, and covered water and feed supplies	Neild et al. (1998)	2006 Merapi (Wilson et al. 2007)	Actions	Pre-event agricultural extension programmes enabled sharing of advice on methods to make farms more economically resilient (by diversifying products). These inadvertently aided in tephra fall mitigation	Marginal conditions pre-event meant that there was no focus on pre-event mitigation for tephra fall or any hazard other than drought and strong winds	Pre-event agricultural extension programmes enabled sharing of advice on methods to make farms more economically resilient (by diversifying products). These inadvertently aided in tephra fall mitigation
					Issues	No tephra fall targeted mitigation programmes in place	Drought the issue most commonly faced, however, most farmers did not have to means to focus on long-term mitigation. However, use of shelter belts due to strong winds increased resilience to tephra fall	No tephra fall targeted mitigation programmes in place

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson		Chaiten
						1991		2008
						Chile Aisen	Argentina Santa Cruz	Chile Los Lagos
					Lessons	Targeted pre-event mitigation planning required. Farmers need to be made aware of available options and methods to minimise losses in future events		Agricultural extension programmes, diversification efforts, and some awareness of Hudson contributed to pre-event mitigation. However, this was predominantly by chance rather than design
2. Preparedness	Knowledge and capacity developed to respond to a event; an areas readiness to respond to an emergency event	Preparedness utilises the assessment of the risk of tephra fall and the vulnerabilities of the exposed farms (identified pre-event). Planning for an event can then be undertaken including organisation of equipment, supplies and personnel. Preparedness plans need to be exercised, evaluated and refined in order to keep them up to date	Haddow et al. (2013), Alexander (2002)	Ruapehu 1995 (Johnston et al. 2000); Kelud 2014 (Blake et al. 2015)	Actions	Some planning in place by agricultural agencies, but not widely understood by farmers		SAG preparedness plans in place. Equipment and organisation of personnel and resources in place for most areas

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson 1991 Chile Aisen	Hudson 1991 Argentina Santa Cruz	Chaiten 2008 Chile Los Lagos
					Issues	No preparedness initiatives on a farm scale		Some issues with ensuring that plans were up to date and well understood
					Lessons	Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies are needed for future events		Continued refinement and evaluation of preparedness plans needed
During event								
3. Communication/ warnings	Strategies in place that provide warnings, notifications, and reports of the evolving situation to the community	Clear, widely disseminated ashfall forecasts that include predictions on spatial distribution and hazard intensities. These need to reach both governmental and municipal level authorities and agricultural agencies. Warnings and forecasts then need to be disseminated to community rural groups and individual farms. Regular updates on the situation are also ideal	Leonard et al. (2008)	Mt. St. Helens (Cook et al. 1981)	Actions	Increased seismic activity was noticed and interpreted as a pre-cursor to eruptive activity by many farmers who had experienced the 1971 eruption. Official warning and evacuations were given a day prior to the eruption	Some warning received at a municipal level, but the majority of farmers in the region were not fully aware	Warnings were received during the initial phase of the eruption, however the focus of these was on ensuring no risk to human life
					Issues	Translation of volcanic information into warnings with appropriate advice was not fully undertaken	No event-specific planning was undertaken for agricultural systems	Timing and focus of warnings was on protecting humans; therefore, many farmers still did not have time to shelter or evacuate animals

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson		Chaiten
						1991		2008
						Chile Aisen	Argentina Santa Cruz	Chile Los Lagos
					Lessons	Warnings need to be either accompanied by or recommend another source of emergency management and mitigation advice	Issues with information transfer from scientists to municipal authorities to agricultural agencies and farmers. Further complicated by inter-country issues	Warnings need to be either accompanied by or recommend another source of emergency management and mitigation advice
4. Response	Actions undertaken to address the short-term impacts of an event. Usually focussed on saving lives, property, and other important assets	Response actions for agricultural systems immediately after a tephra fall event include: livestock evacuation, financial aid, and the supply of supplementary feed	Whitman (2014)	1991 Pinatubo (Newhall et al. 1997); 2010 Tungurahura (Sword-Daniels et al. 2011)	Evacuations	INDAP co-ordinated evacuation of livestock (5000 cattle and 3000 sheep)	INDAP co-ordinated evacuation of livestock (cattle prioritised); animal sales	SAG^ co-ordinated evacuation of livestock (cattle prioritised)

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Hudson		Chaiten
					1991		2008
					Chile Aisen	Argentina Santa Cruz	Chile Los Lagos
					Lack of trucks, low visibility due to tephra fall, and in some areas snow. Authorities and individual farmers questioned the economic feasibility of evacuations. There was also a lack of feed in locations that livestock were moved to and livestock markets became overwhelmed with sales causing a price decrease		The provision of trucks and safe routes was an issue. As the eruption presented a risk of loss of life in a main population centre (Chaiten township), this was the focus of efforts and recourses. Economic viability of livestock evacuations questioned, especially in areas where permanent abandonment was an option

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Hudson		Chaiten
					1991		2008
					Chile Aisen	Argentina Santa Cruz	Chile Los Lagos
					Better planning of transport systems (i.e. provision of trucks) and understanding of locations that livestock can be evacuated to is needed. This will prevent as many farmers feeling compelled to sell livestock, depressing sale prices		Better planning of transport systems (i.e. provision of trucks) and understanding of locations that livestock can be evacuated to is needed
				Financial aid	Credit provided to use for cultivation, animal values paid out in most effected areas	Subsidy based on production change due to eruption, interest-free loans for improvements, supplementary feed for first 8 weeks, grant to replace any animals lost	INDAP* co-ordinated 100 % value of animal paid out, credit for repair work/cultivation (US$500 per hectare-farmer paid then reimbursed by SAG)

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Hudson 1991 Chile Aisen	Hudson 1991 Argentina Santa Cruz	Chaiten 2008 Chile Los Lagos
					–	Marginal conditions pre-eruption meant that some farmers chose to abandon farms rather than accessing aid	Evacuations and abandonments made benefits of aid difficult to understand
					Paying out full values of animals decreased the pressure on evacuations and animal sales	Pre-existing farm conditions and relative vulnerabilities need to be taken into account when assigning aid	Difficulties with rapid, large-scale livestock evacuations was realised, and pay outs for each animal were an effective management tool

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Hudson 1991 Chile Aisen	Hudson 1991 Argentina Santa Cruz	Chaiten 2008 Chile Los Lagos
Post-event								
5. Recovery	Reinstatement and improvement in assets and community resources after an event. Often includes efforts to reduce future risk (contributing to pre-event mitigation efforts)	Assistance (advice, financial aid, and practical support) which allows for farmers to employ the most appropriate of the main recovery strategies recommended for agriculture after a tephra fall event. These include: (1) tephra removal; (2) cultivation of tephra into soil; (3) reseeding of pasture/crop; (4) targeted fertilisation; (5) Rinsing/irrigating of vegetation	Neild et al. (1998), Wilson et al. (2009)		Management advice	Workshops given by INDAP, evacuate where possible initially, cultivation advice given	INTA led workshops, cultivation, and reseeding advised	Farmers advised by SAG to preferably strip off tephra, or cultivate in with disc ploughs
						Relatively poor participation at farmer workshops	Some information was not specific to the semi-arid steppe environment and the low-intensity style of farming	–

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Hudson		Chaiten
					1991		2008
					Chile Aisen	Argentina Santa Cruz	Chile Los Lagos
					Pre-event agricultural extension programmes needed so that relationships are established before an event. This will increase farmer participation in post-event mitigation strategy workshops	Advice needs to take into account the pre-existing farm conditions and the range of farm types.	Successful pre-event agricultural extension programmes, meant that agencies had established relationships with farmers. This aided in trust and transfer of advice after the tephra fall.

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten	PCC-VC	
						2008	2011	
						Argentina	Argentina	Argentina
						Chubut, Rio Negro	Neuquen	Rio Negro
Pre-event								
1. Pre-event mitigation	Prolonged actions taken during 'non-emergency' time to reduce risks to people and property from future hazards	Broadly speaking mitigation actions include land use planning, retrospectively adapting assets to more resilient designs, and hazard-resistant construction and system design. For agricultural systems, this includes farming resilient crops/animals, abandoning the most at-risk land, having shelter available, and covered water and feed supplies	Neild et al. (1998)	2006 Merapi (Wilson et al. 2007)	Actions	Prior to the eruption there had been a focus on encouraging diversification of farming products and methods in the area. This was focussed mainly on drought resilience	No specific mitigation measures in place due to the unique and dispersed nature of the farming. Farmers are used to some losses during winters and other natural events (such as storms) and accept this	Prior to the eruption, there had been a focus on encouraging diversification of farming products and methods in the area. This was focussed mainly on drought resilience
					Issues	Not all farmers wanted to diversify. Many did not have the financial means to do so. Limited awareness of volcanic hazards and risk	No measures in place. Farmers usually do not live on grazing land and do not have frequent contact with livestock	Not all farmers wanted to diversify. Many did not have the financial means to do so

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten		PCC-VC	
						2008		2011	
						Argentina		Argentina	Argentina
						Chubut	Rio Negro	Neuquen	Rio Negro
					Lessons	Farmers with more diverse land use and access to new technologies were more resilient to the tephra fall		Despite unique system, some pre-event mitigation and awareness strategies are needed in such a volcanically active setting	Farmers with more diverse land use and access to new technologies were more resilient to the tephra fall
2. Preparedness	Knowledge and capacity developed to respond to a event; an areas readiness to respond to an emergency event	Preparedness utilises the assessment of the risk of tephra fall and the vulnerabilities of the exposed farms (identified pre-event). Planning for an event can then be undertaken including organisation of equipment, supplies and personnel. Preparedness plans need to be exercised, evaluated and refined in order to keep them up to date	Haddow et al. (2013), Alexander (2002)	Ruapehu 1995 (Johnston et al. 2000); Kelud 2014 (Blake et al. 2015)	Actions	Some emergency preparedness plans in place by INTA (not volcano specific). Some feed supplies stockpiled in case of drought or severe winters		Farming agencies had varying levels of knowledge about the Hudson and Chaiten events and their impacts on agriculture	

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten		PCC-VC	
						2008		2011	
						Argentina		Argentina	Argentina
						Chubut	Rio Negro	Neuquen	Rio Negro
					Issues	Farming agencies had varying levels of knowledge about the Hudson event and its impact on agriculture		Some preparedness plans in place by INTA. Some feed supplies stockpiled in case of drought or severe winters	
					Lessons	Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies is needed for future events		Clear planning, organisation of equipment, personnel training, and evaluation of preparedness strategies are needed for future events	
During event									
3. Communi-cation/warnings	Strategies in place that provide warnings, notifications, and reports of the evolving situation to the community	Clear, widely disseminated ashfall forecasts that include predictions on spatial distribution and hazard intensities. These need to reach both governmental and municipal level authorities and agricultural agencies. Warnings and forecasts then need to be disseminated to community rural groups and individual farms. Regular updates on the situation are also ideal	Leonard et al. (2008)	Mt. St. Helens (Cook et al. 1981)	Actions	No official warning reached the majority of farmers. Municipal authorities were aware of the increased volcanic activity		No official warning reached the majority of farmers. Municipal authorities were aware of the increased volcanic activity	No official warning reached farmers or agricultural agencies. Limited awareness and understanding by municipal authorities

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten		PCC-VC	
						2008		2011	
						Argentina		Argentina	Argentina
						Chubut	Rio Negro	Neuquen	Rio Negro
					Issues	Agricultural agencies and individual farmers were unable to sufficiently prepare. No event-specific evacuation or aid plans could be fully provided		Agricultural agencies and individual farmers were unable to sufficiently prepare. The lack of warning meant that farmers were unable to even place animals in shelter or cover feed and water supplies before the tephra fall began	
					Lessons	Issues with information transfer from scientists to municipal authorities to agricultural agencies and farmers. Further complicated by inter-country issues		Improvement in information transfer from scientists to municipal authorities and agricultural agencies needed. Dissemination of volcanic unrest data through to emergency and response planning vital to minimising impacts. Inter-country communication further complicated the information transfer	

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten		PCC-VC	
						2008		2011	
						Argentina		Argentina	Argentina
						Chubut	Rio Negro	Neuquen	Rio Negro
4. Response	Actions undertaken to address the short-term impacts of an event. Usually focussed on saving lives, property, and other important assets	Response actions for agricultural systems immediately after a tephra fall event include: livestock evacuation, financial aid, and the supply of supplementary feed	Whitman (2014)	1991 Pinatubo (Newhall et al. 1997); 2010 Tungurahura (Sword-Daniels et al. 2011)	Evacuations	No organised evacuations, some animal sales by farmers who felt that they did not have access to enough uncontaminated feed for animals to survive and therefore sold before animal condition deteriorated	No organised evacuations, few sales	Evacuations aided by municipal subsidies	Some animals sold, facilitated by INTA**
						–	–	Implementation of evacuations was usually done at a farm scale, which meant that only those with the financial means to do so were able to evacuate livestock. Evacuation planning did not occur until after the eruption was in progress	

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten 2008 Argentina Chubut	Chaiten 2008 Argentina Rio Negro	PCC-VC 2011 Argentina Neuquen	PCC-VC 2011 Argentina Rio Negro
						–	–	The lack of warning meant that evacuations were unable to be undertaken initially due to unnavigability of Lake Nahuel Huapi	–
					Financial aid	Interest-free loans for improvements (cultivation and shelter mostly), grant to replace any animals lost	Supplementary feed given were requested	Paid out value of each animal by INTA (dead or alive). Municipally organised feed shipped across lake for first few months	400 g of feed per animal, short-term interest-free loans given
						Many farmers chose to sell animals, at relatively low prices before accessing aid	Due to marginal conditions pre-eruption supplementary feed requirements were higher than expected	Numbers of animals were often unknown as farmers withheld numbers for taxation reasons	As the feed rates were calculated per animal, they did not take into account those with increase dietary needs, such as pregnant or lactating animals

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Chaiten		PCC-VC	
					2008		2011	
					Argentina		Argentina	Argentina
					Chubut	Rio Negro	Neuquen	Rio Negro
					Increased understanding of aid available and mitigation options would have been beneficial	Pre-existing farm conditions and relative vulnerabilities need to be taken into account when assigning aid	As the infeasibility of livestock evacuations was quickly realised, pay outs for each animal were an effective management tool	Feed supplies need to be calculated with increased farmer input. Interest-free loans provided good incentive for some diversification or farming and improvement in assets. However, many farmers were unmotivated to make these changes and did not use the scheme

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied		Chaiten		PCC-VC	
						2008		2011	
						Argentina		Argentina	Argentina
						Chubut	Rio Negro	Neuquen	Rio Negro
Post-event									
5. Recovery	Reinstatement and improvement in assets and community resources after an event. Often includes efforts to reduce future risk (contributing to pre-event mitigation efforts)	Assistance (advice, financial aid, and practical support) which allows for farmers to employ the most appropriate of the main recovery strategies recommended for agriculture after a tephra fall event. These include: (1) tephra removal; (2) cultivation of tephra into soil; (3) reseeding of pasture/crop; (4) targeted fertilisation; (5) Rinsing/irrigating of vegetation	Neild et al. (1998), Wilson et al. (2009)		Management advice	Advised to cultivate in tephra to stabilise deposit, use of windbreaks and shelter for animals		Evacuate where possible, shelter animals, and provide alternative water source to lake and streams	Cultivate tephra into soil, vegetate and stabilise tephra deposit, shelter animals, and provide clean food and water
						Some farmers felt unable to follow the advice due to the lack of access to funds and resources and challenges with farming in an area that was marginal pre-event		Dispersed farmer population meant that communication was difficult and visits/workshops challenging to arrange	Many farmers felt that the advice was too late, and many options were constrained by finances and access to resources

Table 6 continued

Management stage	Definition (Haddow et al. 2013; UNISDR 2009)	Optimal tephra risk management actions in agricultural setting	References	Example where successfully applied	Chaiten		PCC-VC	
					2008		2011	
					Argentina		Argentina	Argentina
					Chubut	Rio Negro	Neuquen	Rio Negro
					Advice needs to take into account the pre-existing farm conditions and the resources that farmers have at their disposal		Agricultural agencies were necessarily set up to operate within such as dispersed and unique farming system, such as the Nahuel Huapi National Park. An information transfer system with this in mind needs to be put in place	Strongly benefited from Hudson and Chaiten previously occurring and the recovery lessons and awareness gained from these. Successful pre-event agricultural extension programmes, meant that agencies had established relationships with farmers

^ SAG Servicio Agricola y Ganadero

* INDAP—Instituto de Desarrollo Agropecuario, Chile

** INTA—Instituto Nacional de Technologia Agropecuaria, Argentina evacuated due to the natural cues for all three eruptions. However, beyond these distances effective warnings were not received at local level or farm level for all three eruptions (Table 6). Farmers beyond 20 km from the volcano typically reported that their first knowledge that an eruption had occurred was hearing explosions, sight of a volcanic cloud, or the occurrence of tephra fall. Farmers unilaterally noted that provision of some warning would allow emergency actions to be taken, such as sheltering animals, securing homesteads, and securing water and feed supplies.

4.4.4 Initial response

For pastoral farmers, once tephra began to fall, livestock welfare management became a top priority. Livestock evacuations were used in all three eruptions, but were area and context specific (Table 6). Evacuations were prioritised based on the value of individual animals (e.g. cattle are more valuable than sheep), and implementation at farm scale was initially left to individual farmers. This meant that only those farmers who had the financial means to access transport and alternate grazing land outside the impacted zone were able to evacuate animals. However, in the weeks after the Chaitén and CC-VC eruptions, Chilean officials recognised issues with the feasibility of widespread livestock evacuations and paid farmers compensation based on the value of the animal regardless of whether it survived (Table 6). There was no clear tephra thickness threshold for farmers to be entitled to the subsidy, rather the state of impact on the farms and the condition of the animals was assessed by agricultural agency officers and determined the compensation amount. This often proved more effective than undertaking evacuations, as the lack of available grazing for animals meant they either had to be sold cheaply or expensive rentals paid for grazing land. However, in some cases farmers felt they were underpaid for their animals, particularly in areas where exact animal numbers were not well recorded or 'adjusted' for taxation purposes. Increasingly, there is recognition of the value of livestock as both an economic and psychosocial asset for affected farmers.

4.4.5 Post-event recovery

After the initial emergency period, both pastoral and horticultural farmers requested advice from municipal production managers and agricultural agencies (Instituto Nacional de Tecnología—INTA in Argentina and Instituto de Desarrollo Agropecuario—INDAP in Chile) on how best to recover from the negative effects of tephra deposition. For pastoral farms, the main recommendation given to remediate pasture was to either remove the tephra or cultivate it into the soil. For horticultural farms, rinsing tephra off the crops and building greenhouses and shelterbelts in areas prone to wind remobilisation of tephra deposits were the main advice given (Table 6). Farmers followed this advice to varying levels, primarily dictated by what resources they could access. The areas affected by the CC-VC eruption benefited from the Chaitén and Hudson events, as managers were more aware of the recovery options available, which often led to clearer advice being given. In the semi-arid, steppe region, the majority of farms across all three depositional zones did not have access to machinery for cultivation and soon realised that removal of tephra was not suitable in an area where the deposit was still being remobilised. Financial credit was given to farmers for cultivation and re-seeding (Table 6). In areas that received >300 mm of tephra fall, cultivation or removal was not possible and farmers were forced to wait for more gradual incorporation of tephra into the soil. Cultivation of tephra into the upper soil horizon was consistently found to speed up recovery and aid with pasture reestablishment.

Some farms in the temperate region, after the Chaitén and Hudson eruptions, even reported an increase in pasture growth the following spring after cultivation of tephra into the soil (at tephra thicknesses of 10–100 mm). This has been observed after previous events, such as 1980 Mt. St. Helens (Cook et al. 1981), where farms which cultivated reported more rapid recovery and decreased fertiliser requirements compared to those that left the tephra deposit on top of the soil. Greenhouses (for growing fruiting vegetables such as tomatoes and fruits such as cherries) and shelterbelts (to protect pasture and arable crops) were found to be the most effective at aiding horticultural recovery and building resilience to tephra remobilisation. These methods are the same as those employed in areas that receive multiple tephra fall events per decade, such as agriculture around Merapi (Indonesia), Kelud (Indonesia), and Tungurahura (Ecuador) volcanoes (Blake et al. 2015; Sword-Daniels et al. 2011; Wilson et al. 2007).

In some areas of the Argentine steppe after the Chaitén and CC-VC eruptions, there was confusion around how best to access information and aid money, and in rare cases some hesitance to follow the prescribed advice. Farmers who did not take full advantage of aid packages were those who also had low community connectedness (not part of rural community groups, lacked strong links with neighbours), had not previously participated in agricultural extension programmes, and had little faith in governmental and municipal authorities. This affected their ability to cope with the tephra fall and likely hindered their recovery and exacerbated losses. A consistent theme amongst many of the interviewees was the perception that people in the neighbouring country or province were receiving more aid or had a more positive future. When examined, this often proved incorrect and was more prevalent in those who were unaware of all available municipal mitigation and recovery initiatives.

4.4.6 Recommendations

Overall, there are many management recommendations that can be identified from the three eruptions (Table 6). These include:

- Targeted pre-event planning, including the establishment of agricultural extension programmes, awareness campaigns, and diversification schemes.
- Better organisation of management personnel and equipment, and continued evaluation and refinement of any preparedness plans.
- Clear pathways for information transfer from scientists, stakeholders, and farmers.
- Guidelines to aid decision making around livestock evacuations. These need to include when evacuations will be activated, how they will be transported, and locations livestock can be moved to.
- Increased communication between agricultural agencies and farmers, providing specific advice on how best to aid recovery from tephra fall.

5 Analysis of impacts

The following section presents a set of damage states based on the interview and observational data collected after the three Patagonia events and information collected after previous post-EIA of agricultural areas affected by tephra fall (Sect. 5.1). Damage/production states were created to categorise the impacts that occurred at interviewed farms in

Table 7 Proposed performance-based damage states created to catalogue impacts at the various farm interview sites across the three eruptions

Damage state	Description	Pastoral				Horticultural	
		Large farms (>500 ha)		Small farms (<500 ha)			
		Effects on production	*Damages*	Effects on production	*Damages*	Effects on production	*Damages*
0	No disruption	No production change	*No damage*	No production change	*No damage*	No production change	*No damage*
1	Some disruption	Minimal, absorbed within normal boundaries of fluctuating production (<25 % production loss)	*>75 % pasture available; Some grazing still available*	Supplementary feed required to maintain production (>15 % production loss)	*<75 % pasture available; Pasture available not enough to sustain livestock*	Slightly lower productivity but recoverable harvest	*<75 % vegetation covered*
2	Moderate disruption	Some supplementary feed required, adverse health effects in exposed animals (~25–50 % production loss)	*~50 % pasture available; Pasture available not enough to sustain livestock*	Large amount of supplementary feed required (15–50 % production loss)	*60–40 % pasture available; Most animals unable to graze, animal deaths begin, open water sources contaminated*	<25 % production loss	*Some plant breakage and damage to crops; possible acid burns and abrasion*
3	High disruption	Total reliance on supplementary feed, widespread animal sales and evacuations (>60 % production loss)	*<25 % pasture cover; Animals unable to graze due to tephra cover*	Entire season production lost, discontinuation of normal farm activities (e.g. mating, shearing, etc.) (>50 % production loss)	*Animals unable to graze due to tephra cover, majority of animals dead, in poor condition, or sold, basic soil fertility indicators (N, P, K) negatively affected*	Rinsing/mitigation needed, ~50 % production loss	*Most crops sustained some damage*
4	Total loss of capabilities	Widespread mitigation and rehabilitation needed in order for production to resume (>70 % production loss)	*Very low likelihood of soil recovery in the next 12 months, >50 % animal deaths*	No production possible for at least one year (>70 % production loss)	*Total abandonment of farm—often permanent, vegetation dead*	>70 % reduction in yield; >1 season to recover	*All crops damaged in some way; damage to greenhouses*

order to convert the qualitative interview data into a scaling system, which will then be compared to different HIM (Sect. 5.2) and VC (Sect. 5.3).

5.1 Damage/production states

Damage/production states were developed by assessing the factors that influenced agricultural losses predominantly using interview data from the three case studies presented here, as well as previous impact assessment case studies (Table 7). These factors included production base losses (e.g. livestock illness and death for pastoral, crop losses for horticultural), external assistance (e.g. supplementary feed, evacuations, cultivation, and/or mitigation assistance), and overall productivity losses. These factors were separated into a damage/production state scale based on theoretical steps in damage, impacts, and production losses observed elsewhere (Supp. Mat. 1), and production losses associated with different impacts after the three Patagonian eruptions. Five main states of damage were identified using the factors described above and associated production changes, which are presented in Table 7. Five damage/production states (DPS) were chosen in order to classify farms with no impacts (DPS0), farms with some impacts that could economically recover with minimal external assistance (DPS1), farms that needed varying levels of assistance (DPS2 and 3), to farms that could not longer operate at all (DPS4). The damage/production states were designed to be applied at a farm scale in order to address all damage and changes in the productivity of pastoral and horticultural farms. The pastoral farm damage/production states are separated into two scales, as different farming practises occur on different sized farms which affect vulnerability to tephra impacts. Smaller farms are also less likely to be creating a substantial profit margin pre-event (compared to larger farms of the same type and intensity), which leaves them more vulnerable to production losses. Horticultural farms were not split into small and large farm groups as they were found to be more homogenous.

For pastoral farming, the end members of the scale represent no damage and maximum possible damage, where DPS0 is a farm that is completely unaffected by tephra fall (production loss change within what can occur over farm cycle) and DPS4 is a farm that suffers damage that is severe enough to completely halt production. The division of the intermediate states of damage (damage/production states 1–3) is predominantly based on productivity levels and the expected time and steps needed to recover to pre-event production. At DPS1 (some disruption), productivity losses are up to 25 % for large farms and up to 15 % for small farms. The majority of farms are assumed to recover to pre-event production levels within a year. At DPS2 (minor disruption), productivity losses are up to 50 % and it is assumed that they will take >1 year to fully recover. At DPS3 (high disruption), productivity losses are usually greater than 70 % and large numbers of animal deaths, sales, and evacuations occur and mitigation measures will occur before productivity returns to pre-eruption levels (Table 7).

Damage/production states for horticultural farming are less robust due to the smaller number of farm sites within this study, but rely primarily on productivity changes following tephra fall. Horticultural farms within DPS0 will not suffer any production losses, and DPS1 will sustain losses that can be recovered within a season, whereas DPS2, DPS3, and DPS4 will sustain up to 20, 50, and 70 % production losses, respectively (Table 7). There was not a wide range of damage/production states presented in the horticultural farm sample, as most farms were located primarily within the same geographic zone (usually in the transitional zone between temperate and semi-arid, where rainfall is still greater than 250 mm/year, but not in the Andean region), and therefore received similar thicknesses of

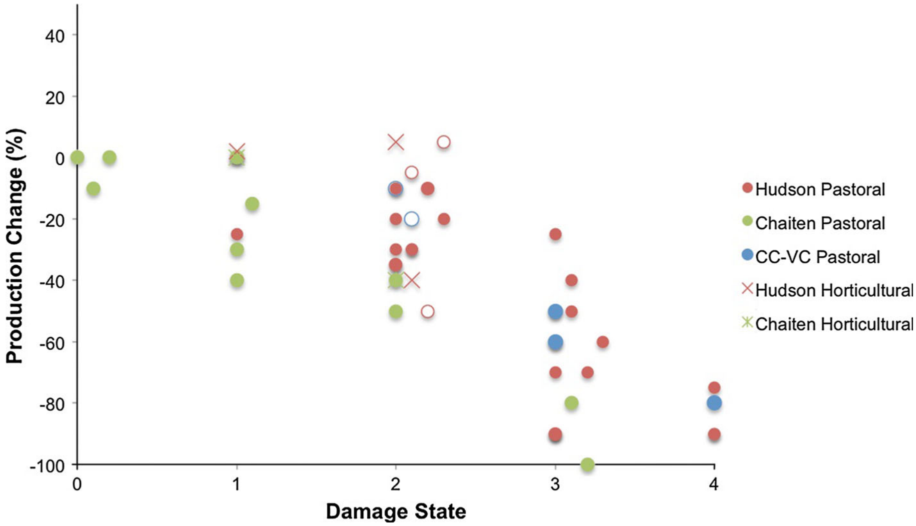

Fig. 6 Damage state data with agricultural production change across the three eruptions for pastoral and horticultural farms. *Open symbols* show farms where livestock evacuations took place

tephra fall. This accounts for the more arbitrary scale based on production losses, rather than the stronger theoretical and observational basis for the pastoral scale.

This scale was applied to the pastoral and horticultural farm sample visited across the three events and compared to percentage production changes (Fig. 6). Due to the retrospective nature of the study, damage/production states were applied using production change data, in addition to the observed impacts. However, if applied to future events the states could be assigned based solely on descriptors and give some indication as to the associated production losses that may occur.

5.2 Hazard intensity measures

As it is most commonly recorded (Jenkins et al. 2014b; Wilson and Kaye 2007), tephra deposit thickness (mm) was used as the main HIM in this study. Therefore, the relationship between tephra thickness and the occurrence and severity of damage was investigated.

On average, tephra thicknesses taken immediately after the initial deposition provided some indication of animal deaths and production losses within each climate zone, particularly in the temperate zones. There is likely to be uncertainty with these data points, particularly noting that estimates of tephra thickness have large uncertainties due to post-deposition compaction and remobilisation which can occur quickly and often before consistent field measurements can be obtained (Macedonio and Costa 2012) and the reliance on farmer recollection for livestock casualty estimates which could be subject to conscious or unconscious bias (Table 8). Prolonged (months to years) wind remobilisation of tephra was reported to greatly compound impacts at all farms across all three eruptions. When case study farms are aggregated across the study areas and ranked in order of decreasing tephra thickness, the exposed farms within the temperate zones for Hudson and Chaitén show a decrease in animal deaths and production loss (Table 8). This decrease in loss with decreasing thickness is not as evident for farms in semi-arid areas where tephra

Table 8 Average regional animal death (%) and production change (%) from aggregated interview data within the temperate and semi-arid climatic zones ranked by tephra thickness

	Climate zone	Location	*n*	Maximum tephra thickness (mm)	Mean tephra thickness (mm)	Minimum tephra thickness (mm)	Maximum animal deaths (%)	Mean animal deaths (%)	Minimum animal deaths (%)	Maximum production change (%)	Mean production change (%)	Minimum production change (%)
Hudson	Temperate	Ibanez Valley	5	1000	600	100	100	70	38	−100	−75	−40
		Cerro Castillo	6	100	100	70	100	60	0	−80	−45	−20
		Puerto Ibanez	6	40	50	40	91	30	0	−80	−40	−15
	Semi-Arid	Chile Chico	5	100	100	100	50	30	0	−40	−10	0
		Los Antiguos	4	80	80	80	100	40	0	−25	−30	5
		Tres Cerros	1	NA	40	NA	NA	90	NA	NA	−90	NA
		Puerto San Julian	1	NA	5	NA	NA	NA	NA	NA	−80	NA
		Rio Gallegos	1	NA	1	NA	NA	20	NA	NA	−10	NA
Chaiten	Temperate	Chaiten	5	300	300	150	100	40	0	−100	−63	−15
		Futaleufu	3	150	150	150	0	0	0	−40	−25	−10
	Semi-Arid	Esquel	2	5	5	5	0	0	0	0	0	0
		Pilcaniyeu	3	5	5	5	10	5	4	−10	−10	0
CC-VC	Temperate	Nahuel Huapi	2	350	350	350	0	2	3	−20	−15	−10
	Semi-Arid	Jacobacci/ Comallo	3	50	47	40	73	38	17	−80	−63	−50

NA—Only one farm interview conducted within these regions

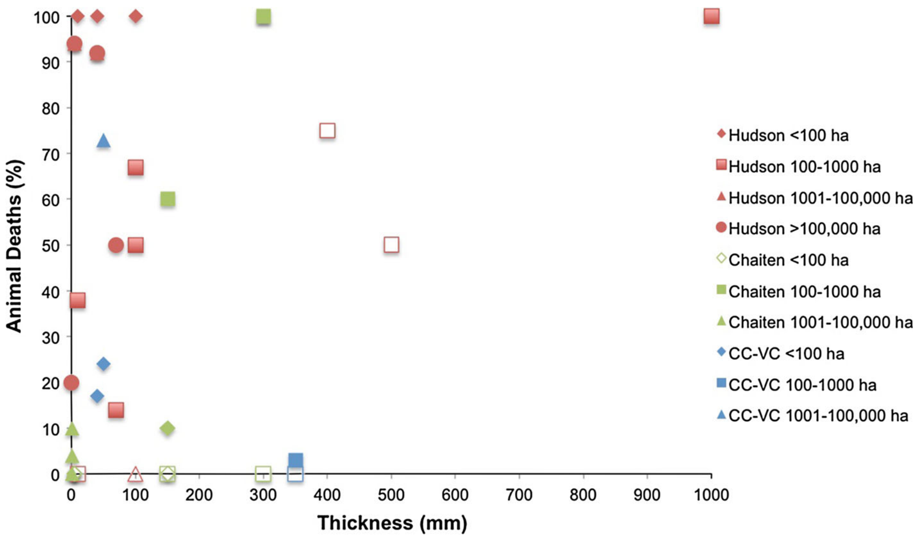

Fig. 7 Animal loss percentage with tephra thickness for various sized farms [in hectares (ha)] across the three eruptions. *Open symbols* show farms where livestock evacuations took place

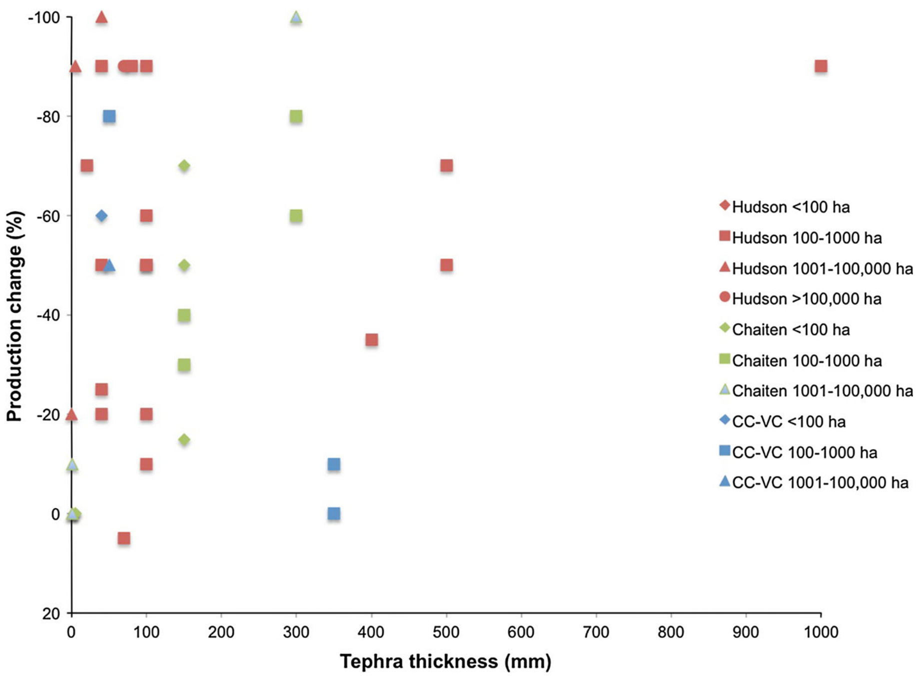

Fig. 8 Farmer perception of productivity change for various sized farms [in hectares (ha)] after the three eruptions with tephra thickness

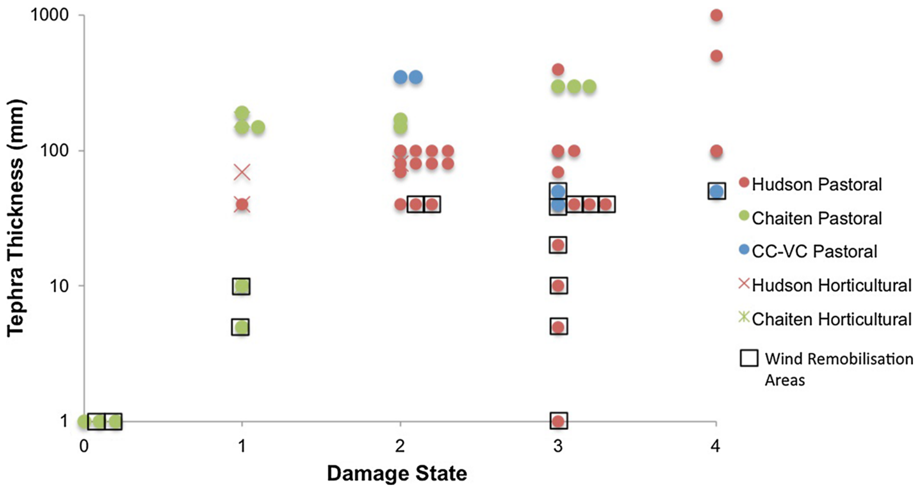

Fig. 9 Damage state data for pastoral and horticultural agriculture across the three eruptions with initial recorded ashfall thicknesses

thickness still has an influence on impacts, but the importance of wind remobilisation of tephra in compounding impacts becomes more evident.

However, when the data are not aggregated by region, tephra thickness alone was not a good predictor of animal deaths (Fig. 7) or production change (Fig. 8), with no clear relationship observed, especially at less than 200 mm thickness. This suggests that at these thicknesses, there are likely other factors that determine losses (i.e. other HIM or VC). It is likely that these factors (especially VC) are more homogenous within regions accounting for the clearer trend in impacts with thickness on a regional scale (Table 8).

Tephra thickness was also tested as a predictor of damage/production states, which better capture qualitative impacts, likely recovery times, as well as production changes. Damage/production states show some relationship with tephra thickness (Fig. 9). This is more pronounced when the data are separated into farms in the temperate and the semi-arid zones. This suggests that whilst thickness has some limitations when considering impacts across diverse regions, it does have some utility within climatically similar regions (and in turn other VC, such as pre-existing animal and farm intensity differences). The relationship between tephra thickness and impacts is also more evident when areas of different tephra fall duration and remobilisation severity are separated (in the semi-arid area wind remobilisation of tephra deposits over months–years after the eruption intermittently made conditions similar to continuous tephra fall events). Average thicknesses associated with each damage/production state show that an increased damage/production state occurred at lower thicknesses in the semi-arid region (~130-mm tephra to reach DPS1) compared to temperate areas (~10-mm tephra to reach DPS1) (Table 9a). Despite the apparent relationship between tephra thickness and DPS, no fragility functions are proposed. This is due to the large range of tephra thicknesses observed within each of the proposed DPS levels, the lack of trend when considering the dataset as a whole, the lack of constraint on the interface between DPS0 and 1, and the number of points available when dividing the data into various climatic zones and farming styles (i.e. into the various vulnerability characteristics) not allowing statistically robust functions to be calculated.

Table 9 Mean tephra thicknesses (and standard deviations) for all impact data in each impact class. Data are classified by vulnerability characteristics: (A) climatic zone; (B) farm type; and (C) access to irrigation/cultivation machinery

Damage state	*n*	DS0	DS1	DS2	DS3	DS4
(A) Temperate						
Mean tephra thickness (mm)	28	–	130	130	225	535
Standard deviation (mm)		–	60	100	130	400
Semi-arid						
Mean tephra thickness (mm)	21	1	10	40	25	75
Standard deviation (mm)		0	5	0	20	35
(B) Pastoral						
Mean tephra thickness (mm)	37	5	110	110	120	410
Standard deviation (mm)		0	70	30	145	380
Horticultural						
Mean tephra thickness (mm)	8	–	40	150	–	–
Standard deviation (mm)		–	–	40	–	–
Mixed						
Mean tephra thickness (mm)	4	–	–	150	300	–
Standard deviation (mm)		–	–	35	–	–
(C) Access to irrigation and cultivation machinery						
Mean tephra thickness (mm)	17	5	125	85	250	750
Standard deviation (mm)	17	0	55	10	190	250
No access to irrigation and cultivation machinery						
Mean tephra thickness (mm)	32	–	5	160	70	180
Standard deviation (mm)	32	–	5	110	90	190

Thicknesses are rounded to the nearest 5 mm

Blank squares show where not enough data points with the applicable VC were observed within that DPS

Although the number of HIM included in the comparative analysis was limited, some conclusions can, nonetheless, be drawn and insights emerge. Tephra thickness remains the property most likely to indicate the damage/production state of the affected area (and therefore severity of impacts) during post-event assessment and when developing forecasting capacity with pre-EIA and risk assessments. Tephra thickness is an especially important predictive measure when considering impacts at a regional scale rather than on a farm-by-farm basis where a holistic understanding of individual farm operations and assets may not exist. Using tephra thickness to predict the damage/production state (a cruder measure of impacts) of the affected area appears to be more accurate than using specific loss information such as animals deaths or production losses. However, caution is needed when only using tephra thickness, because the clear differences between the temperate and semi-arid results demonstrates the importance of taking into account VC and other properties of the exposed systems. Additionally, it is also important to acknowledge that tephra thickness measurements may not accurately represent the distribution of tephra at the time of deposition. Reworking of the tephra deposit through compaction and remobilisation can often occur within hours of deposition. This means that the length of time after the eruption that a tephra thickness measurement is taken is also important. This study used approximations of the maximum tephra thicknesses received; however, it is likely that these values did not remain static in the days and weeks after the eruption, causing additional uncertainties.

5.3 Vulnerability characteristics

In order to evaluate the influence that the VC of a farm has on impacts, the tephra thickness thresholds for each damage/production state were compared to farms with different vulnerability characteristics (Table 9). This allows the identification of the relative influence each VC has on farm vulnerability to tephra fall. The VC evaluated were:

1. The climatic zone the farm is located in (Table 9a);
2. Farm type (Table 9b);
3. Access to irrigation/cultivation machinery (Table 9c).

The importance of seasonality (i.e. the season the tephra fall occurred in) was also assessed. However, the lack of variety in the data points (all three eruptions occurring in late autumn or winter) did not allow for comparison of damage/production state tephra thickness thresholds. These VC were assessed, as they all have appeared to influence impacts after previous events (Table 5), were consistently recorded during interviews, and can be easily recorded in future post-EIA.

Whilst average tephra thicknesses (and standard deviations) have been calculated for the DPS scheme with various VC (Table 9), no normally distributed fragility functions are proposed. This is due to the inability to accurately quantify the probability and associated error of each of the DPS scheme categories occurring at a given tephra thickness. This uncertainty and the number of data points when divided into groups of corresponding VC mean that the creation of fragility functions is potentially misleading.

5.3.1 Climatic zone

Observed agricultural impacts were also strongly influenced by climatic zone. Farms in the temperate, Andean zone did not experience the same widespread, long-term wind remobilisation of tephra deposits as those on the semi-arid, Argentine steppe. Severe impacts to vegetation and animal health were often seen at comparatively thin tephra fall depths (DPS3 and 4 were reached at 25 and 75 mm, respectively, compared to 225 and 535 mm, respectively, in the temperate zones; Table 9a). Additionally, lower standard deviations for the thickness thresholds in the semi-arid region (compared to the temperate area) show the strong control that the semi-arid environment will have on impacts. Large standard deviations in the temperate zone likely imply that other VC will also strongly influence the tephra thicknesses at which impacts occur (Table 9a). Wind remobilisation of tephra deposits prolonged impacts to vegetation and livestock by reburying pasture and crops, and continuously contaminating feed and open water supplies. For example, average overall farm production losses after the CC-VC tephra fall for interviewed farms in Jacobacci (semi-arid) were ~60 % despite receiving less than 60 mm of tephra; in contrast, farming within the Nahuel Huapi National Park (temperate) received more than 300 mm of tephra but only experienced overall farm production losses of ~15 % (Supp. Mat. 4). This pattern was observed across all of the three Patagonian events with semi-arid areas (≤250–500 mm/year rainfall), where production losses and animal deaths occurred even in areas where less than 3–5 mm of tephra was deposited (Supp. Mat. 4, 5 and 6).

The climate (in particular precipitation levels) was also important due to the interconnectedness of the other VC of a farm with the climatic setting. As farming within the semi-arid steppe was marginal pre-eruption, low-intensity farming took place and farms had little access to 'improvement' assets. Another VC influenced by climate was the pre-existing condition of animals and crops, which determined their resilience to the effects of tephra fall. Animals in the steppe region were often slightly malnourished compared to those in the temperate zone. Climate is also a valuable predictive tool as areas of low rainfall where wind remobilisation of tephra deposits occurred (usually <250 mm/year) can be identified pre-eruption. The role of wind speed in remobilising tephra may also be a valuable predictor, with wind speeds in the steppe region higher than in the temperate zone (Fig. 5). These factors left farms in the semi-arid region vulnerable to negative impacts due to tephra fall, resulting in relatively low tephra thicknesses causing high damage/production states compared to the temperate region (Table 9a).

5.3.2 *Farm type*

The type of farming is also important, as different types of farming were more or less resilient to the tephra fall. Horticultural farmers, particularly in Chile Chico and Los Antiguos following the Hudson tephra fall, usually experienced a much lower decrease in production than their pastoral counterparts, despite being exposed to comparable tephra fall thicknesses and subsequent wind remobilised tephra. These horticultural farms had access to irrigation and cultivation equipment, which aided tephra stabilisation and incorporation into the soil. The coarser grain size of the tephra compared to the soil in those locations also reduced soil water retention, increasing irrigation demand (Wilson et al. 2011a). Pastoral farms by comparison did not cope well relying on natural (i.e. non-assisted) pasture recovery, especially where wind remobilisation of tephra was prevalent. The most resilient were mixed farms utilising both livestock and crop production. This diversity meant farmers could adapt to focus on the most productive sources of income. Whilst diversification of production was a key focus of local agricultural agencies, many areas (particularly the steppe) simply could not adapt due to lack of access to irrigation water supply.

Although the majority of farms assessed for this study were pastoral, it appears that horticultural and mixed (pastoral, arable and/or horticultural) were more resilient to the tephra fall. This is demonstrated by the higher tephra thicknesses required to cause more severe damage/production states (Table 9b). This resilience is likely due to horticultural farms having access to 'improvement' assets such as cultivation, irrigation, and fertilisation machinery. Additionally, some horticultural farming in the region was confined to greenhouses that protected the crop from tephra fall contamination.

5.3.3 *Access to 'improvement' assets*

Pastoral farms that had access to clean feed, clean water, and shelter for animals, and horticultural farms with greenhouses and irrigation systems suffered fewer impacts than farms that did not have these 'improvement' assets. Farms with access to cultivation machinery to mix tephra into soil also recovered more rapidly and sustained lower overall production losses. These assets helped to mitigate impacts and particularly fostered a more rapid recovery. Typically, farms in the semi-arid region were less likely to have access to improvement assets prior to the tephra fall as they used a low-intensity, extensive farming model. However, a few farms in the region already had some shelter for animals and greenhouses for crops due to previous issues with strong winds, soil erosion, and sometimes snow. These were able to be used to shelter animals from tephra fall and wind

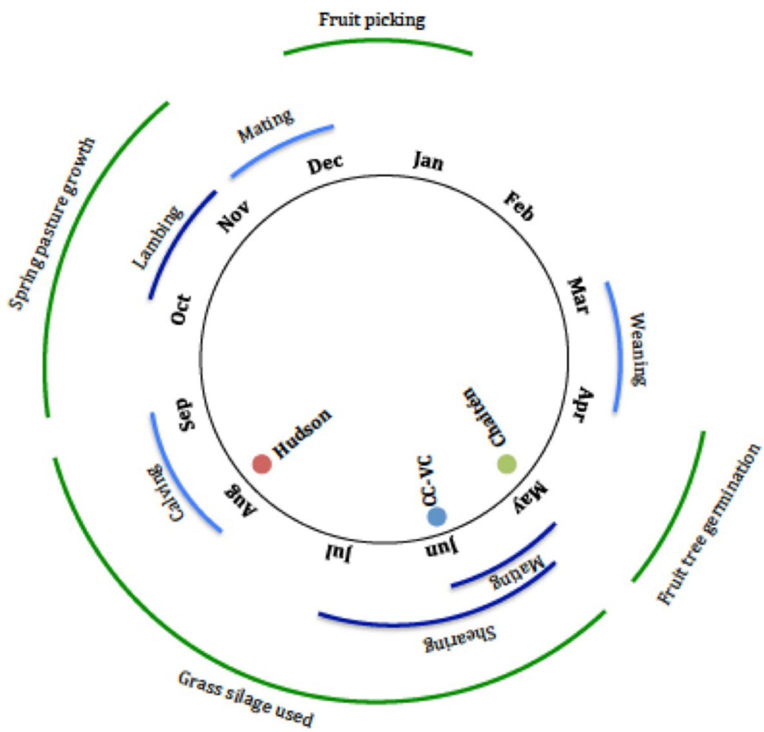

Fig. 10 Seasonal occurrence of eruptions and corresponding farm activity. *Centre points* show tephra fall start dates, pale *blue lines* representing cattle, *dark blue lines* representing sheep, and *green lines* representing vegetation cycles

remobilisation. Pastoral farms that had shelters in the semi-arid region around Pilcaniyeu (after Chaitén) and Jacobacci (after CC-VC) experienced much lower losses than farms in the same region without shelter ($\sim$15–20 % lower animal deaths). Similarly, horticultural farms that used greenhouses in the Chile Chico region (1991 Hudson eruption) could continue production mostly uninterrupted despite 100–200 mm of tephra and severe wind remobilisation of tephra (Wilson et al. 2011a). Where greenhouses were not utilised in the temperate zone, cultivation machinery was used to stabilise the tephra deposit by incorporating it into soil or extensively irrigating to dampen and stabilise tephra deposits. These improvement assets and treatments were unaffordable or impractical to use in the large, extensive farms in semi-arid areas. This further exacerbated the divide between the climatic zones and their associated impacts.

The influence that the accessibility of machinery for cultivation/irrigation had on impacts is demonstrated by the damage/production state tephra thickness thresholds (Table 9c). Farms with no access to machinery reached DPS4 at a mean tephra thickness of only 180 mm, whereas those farms that were able to immediately begin irrigation and cultivation needed an average of 750 mm of tephra to reach DPS4, this trend was also observed for DPS1 and DPS3 (Table 9c). This demonstrates the importance of investment in ‘improvement’ assets as a pre-event mitigation strategy, as in having access to irrigation/cultivation, the vulnerability of the farm to damage is decreased substantially.

5.3.4 Seasonality

The season and thus what farm processes were occurring at the time that the tephra fall occurred were also influential in determining the impacts that occurred on a farm. In the Hudson tephra fall zone, cattle and sheep were in late-stage pregnancy, increasing their energy requirements and thus vulnerability. Farmers were also eagerly awaiting the spring growth period as feed stocks were dwindling and animal condition poorer than during the summer months (Wilson et al. 2011a). A similar issue occurred in the CC-VC region where farmers were near the beginning of winter and grazing relief in the form of spring growth was still a few months away. This put pressure on feed supplies usually used to supplement animal grazing during the winter. The Chaitén eruption occurred earlier in the year (early May, at the end of autumn) at a time when feed supplies were higher (Fig. 10). However, wool length amongst sheep was at its longest and shearing was about to commence. Tephra clogged fleeces, abraded shearing equipment, and reduced the number of animals shorn per hour. This led to a 25 % decrease in the volume of saleable wool in some areas. Horticultural farms also had different levels of vulnerability to the tephra fall dependent on the type of crop and the time of year. After the Chaitén eruption, cherry and other fruit trees were dormant and so experienced few if any impacts compared to the severe impacts experienced by cherry farmers in Los Antigos and Chile Chico from tephra remobilisation during spring and summer periods when trees were blossoming and fruiting.

The three Patagonian events demonstrate the importance of recording VC information when predicting and minimising impacts to agriculture, especially when considering impacts over a smaller scale where thickness and other HIM could be very similar, but the impacts between farms could differ due to specific VC. Due to this influence that VC has on impacts and relative damage/production states, it is that these are captured in both pre- and post-EIA.

5.4 Recovery

The recovery of agricultural areas after a tephra fall was assessed to highlight which HIM and VC are slowing agricultural rehabilitation and also to demonstrate which mitigation techniques accelerate the return to normal production levels. Recovery patterns were assessed by comparing damage/production states at the time of maximum losses (within 6 months after the eruption), with the damage/production states observed when interviews were conducted (197 months after the initial eruption for Hudson, 9 and 46 for Chaitén, and 9 months after for CC-VC) (Fig. 11). This showed that damage/production states in the semi-arid areas all remained elevated for much longer than those in the temperate zone. After over 16 years, farms in the temperate region (<200 km from the vent) affected by Hudson tephra falls have mostly returned to damage/production state one in the region where tephra falls were greater than 400 mm and zero in areas with smaller thicknesses. However, farms in the semi-arid area, which received much less tephra, have not returned to a damage/production state of zero even after many years (Fig. 11a). A similar trend was also observed after the Chaitén and CC-VC eruptions where damage/production state rebound did not occur as rapidly in the semi-arid zones (Fig. 11b, c, area beginning >100 km from vent for Chaitén, >80 km for CC-VC).

The mitigation, aid, and advice given will also have a large influence on the recovery time. In order to compare aid given across the three eruptions, management actions were split into five categories (Fig. 11). Level 0 meaning no aid or assistance, level I showing

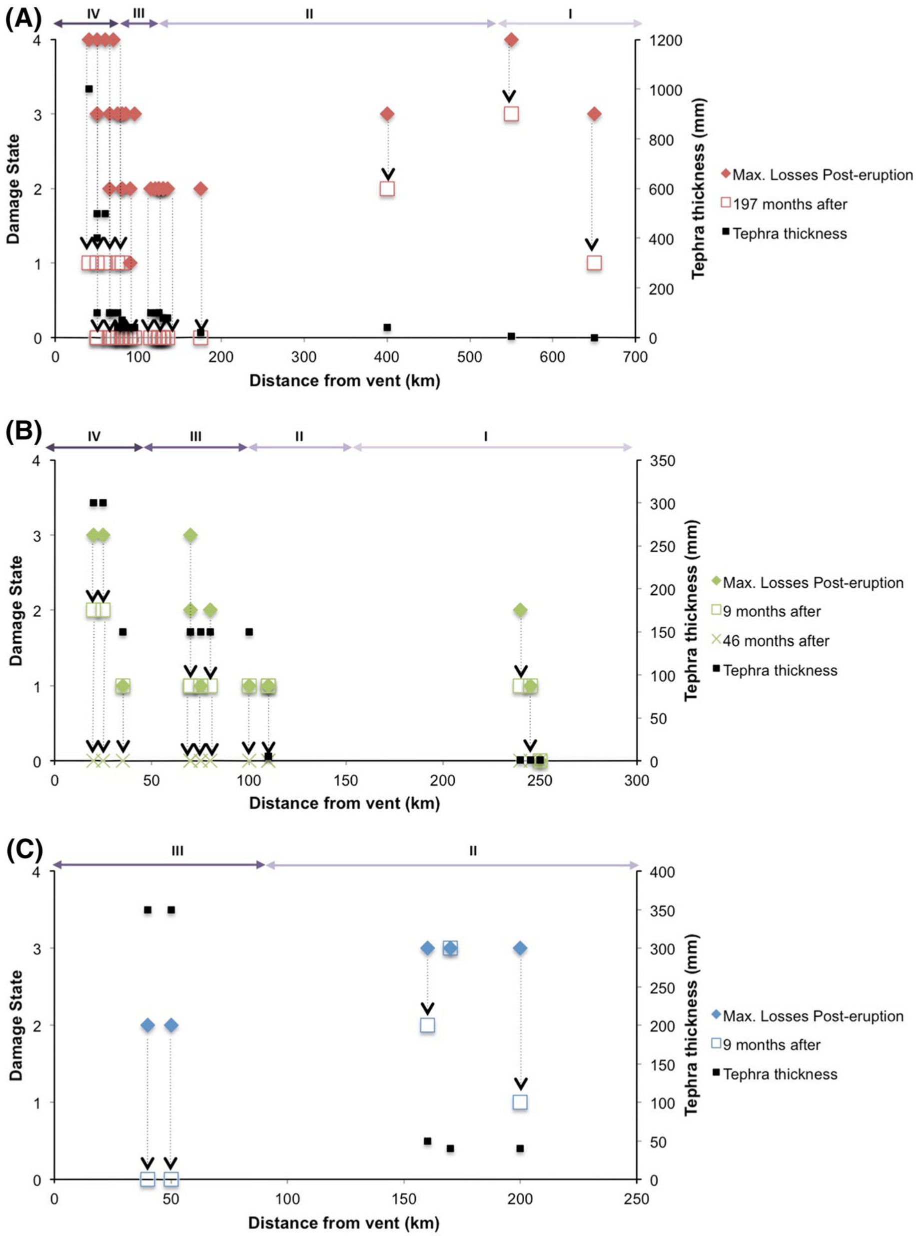

Fig. 11 Agricultural recovery assessment using damage states recorded at time of maximum loss, and subsequent visits for **a** Hudson, **b** Chaiten, and **c** CC-VC. Recovery and management categories for areas annotated, with level 0 meaning no aid or assistance, level I farms was given supplementary feed, advice, and/or interest-free loans/tax breaks; level II was farms where a percentage of animal value was paid out and feed supplies were given, along with subsides and grants for recovery; level III was where total animal value was paid out, allowances for recovery were given on a per hectare basis, and subsidies and loans were widely available; and level IV being where 100 % of land and animal value was paid out

farms were given supplementary feed, advice, and/or interest-free loans/tax breaks; level II was farms where a percentage of animal value was paid out and feed supplies were given, along with subsides and grants for recovery; level III was where total animal value was paid out, allowances for recovery were given on a per hectare basis, and subsidies and loans were widely available; level IV is where 100 % of land and animal value was paid out. Areas in level IV were all within 100 km of the vent and had high damage/production states, usually due to the very thick tephra fall deposits received. Farms within this area showed a decrease in their damage/production states within 9 months (for Chaitén and CC-VC, Fig. 11b, c) despite these thicknesses. In contrast, areas that received level I and II assistance did not always return to damage/production state zero, despite having lower maximum damage/production states than farms in level IV (Fig. 11). This demonstrates the importance of practical aid solutions in agricultural recovery.

In order to increase understanding of agricultural recovery after tephra fall and allow for better identification of effective mitigative strategies, longitudinal studies need to be undertaken. Longitudinal study sites need to be selected to consider a range of farm types and intensities, as well as a broad cross section of hazard intensities. They also need to be systematically assessed using robust methods over a period of months to years after the tephra fall event to understand the complete recovery process.

6 Lessons for future impact assessments

This study strengthens previous knowledge on the importance of considering the hazard properties (HIM) when forecasting or assessing tephra fall impacts and also integrating information on existing farm conditions and vulnerabilities (VC). This needs to be considered both pre-eruption when identifying areas of vulnerability and methods to increase resilience, but also post-eruption when assessing the occurrence and distribution of impacts in order to plan management. This holistic approach to risk assessment will ensure that risk models are more accurate and more widely applicable in the future.

Vulnerability characteristics of a farm can be identified pre-event. This means that high losses in areas of relative vulnerability can be planned for and management plans and farmer education can be put in place. Areas such as the Argentine steppe and other low rainfall (<250 mm/year) volcanic areas are likely to experience tephra remobilisation after an eruption. Awareness of tephra deposit stabilisation measures and plans to access machinery and materials to do this could minimise future losses and speed up recovery.

The proposed DPS scheme and the associated average tephra thicknesses (Table 9) could be applied in future, scenario-based, pre-EIA for the Patagonian region. If a tephra deposit scenario is created or an event has just occurred and impacts have not yet fully manifested, the DPS tephra thickness thresholds could potentially be applied to farms to estimate likely impact. This could be undertaken for farms in the region where the climate zone, farm type, and access to improvement assets are known, allowing for the correct DPS tephra thickness threshold to be matched and a DPS prediction given. However, a drawback of this is the inability to represent the multiple VC of a farm (e.g. no thresholds are proposed for different combinations of climate and farm types, etc., due to data availability). Additionally, thresholds were calculated using data exclusively from the three Patagonian events and therefore have limited applicability for other tephra falls and may be inappropriate for use outside of the region. However, the broader application of the DPS scheme and the identification of further trends in HIM, VC, and agricultural impacts will allow for greater use of the proposed DPS scheme in simplistic pre- and post-EIA. We suggest application of the DPS scheme to similar agricultural settings elsewhere is a potential area of useful future research, although we note this should be cautiously applied and be subject to rigorous consideration and evaluation.

Whilst no single HIM or VC could accurately predict impacts for these three events, prolonged wind remobilisation of tephra deposits and the associated climatic conditions are a vital VC of the affected system. Initial tephra thickness proved an inaccurate predictor of loss that led to less aid being allocated in areas that then subsequently suffered greater losses than expected (i.e. semi-arid steppe region). Future emergency management and recovery planning need to take this into account as it likely that other tephra fall events will have impacts that can be better constrained with another HIM or VC in addition to tephra thickness.

7 Conclusions

The Hudson, Chaitén, and CC-VC eruptions provide an opportunity to study the different impacts, and controls on impacts, to agricultural systems in the Patagonian region. The area is unique in that three large silicic eruptions in the last 25 years have occurred within 600 km of each other, and all have tephra plumes and affected areas following along the same west-east environmental gradient. The following conclusions can be drawn from the three Patagonian events:

1. Agricultural impacts in the semi-arid, Argentine steppe, across the three events, were more severe than expected considering the relatively low initial tephra thicknesses received (<100 mm). This is because of the low-intensity farming in challenging environmental conditions where there is not always access to 'improvement' assets. This leaves farms vulnerable to tephra fall impacts.
2. Agricultural damage/production states for tephra fall were developed using previous case studies, and interview data and production losses from the three Patagonian events. This allowed for impact data to be categorised into a standard framework and tephra thickness thresholds to be assigned for each state. These thresholds were more robust (i.e. had greater predictive power) when farms were separated into temperate and semi-arid regions, illustrating the importance of considering climate when predicting agricultural impacts.
3. Analysis of farm damage/production states with tephra thickness and influential VC led to the following conclusions:
    a. The complex interaction of HIM and VC of the exposed area will determine the impacts to agricultural systems after tephra fall.
    b. Both the HIM and VC of an area need to be understood and where possible quantified, in order to provide accurate pre- and post-EIA.
    c. This study also identified that the most influential (and easily measurable) HIM when predicting agricultural impacts is tephra thickness. However, tephra thickness alone is an insufficient predictor of impacts.
    d. When considering the VC which determine impacts, climate (and the corresponding tephra remobilisation potential), farm type and size, and access to farm 'improvement' assets were found to be important predictors of impacts. These VC could be identified pre-event to indicate areas that may need more aid or targeted mitigation.

e. The proposed damage/production state scheme and tephra thickness thresholds could be applied to other events, during both pre- and post-EIA, to quantify and monitor impact information, which can inform management strategies.

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