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Changes in volcanic hazard exposure in the Northwest USA from 1940 to 2100

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Abstract This investigation frames volcano disaster potentialities for the US Pacific Northwest by assessing the interaction of the region's growing population and affiliated housing development with volcanic hazards. Changes in human and residential exposure to the hazards are measured for a period of 1940 through 2100 by employing fine-scale (100 m) historical, current, and forecast demographic data derived from a spatial allocation model. Forecast population and housing unit density data from the model are based on societal change scenarios generated by Intergovernmental Panel on Climate Change. This ensemble approach reveals variations and uncertainties in the future hazard exposures, illustrating an envelope of volcano disaster possibilities. The demographic data are evaluated using a three-step, worst-case, downscaling approach by first calculating possible regional impacts before measuring volcano proximal and, thereafter, local hazard consequences. Results indicate that the Northwest regional study area is forecast to experience as much as a 445 % increase in total population and 1336 % amplification in housing unit counts from 1940 to 2100. The Mount Rainier proximal and local hazard analyses reveal the greatest overall increase in the total population and housing units for the entire period of record, whereas the Glacier Peak proximal and local hazard zone are forecast to experience the greatest percentage increase in population and housing units. These findings may be used by emergency managers, land planners, insurers, decision makers, and the public to discover changes in volcanic hazard risk and exposure within their communities, as well as assess potential mitigation and sustainability options.

Keywords Hazards · Exposure · Volcano · ICLUS · SRES

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1 Introduction

An underlying and important driver of increased geophysical disaster occurrences and consequences is the growth in exposure—i.e., populations, built-environments, and assets that may be affected by a hazard (Morss et al. 2011; Ashley et al. 2014). Within the past 80 years, which is the lifespan of an average person in the USA, the conterminous population has more than doubled, and the developed land footprint has amplified by over 600 %. This amplification in population and affiliated development has placed increasing numbers of people and their possessions in harm's way. Change in exposure is not uniform in space or time; indeed, populations have a tendency to cluster in locations promoting urban and suburban development types. These urban population density land uses represent over 80 % of the total US population and continue to outpace the overall national growth (Census Bureau 2012).

The US Pacific Northwest and associated major cities of Portland, OR and Seattle, WA, are prime examples of the considerable growth that many regions and urban areas have experienced during the twentieth and early twenty-first centuries. Based on Census Bureau assessments, the Pacific Northwest's residential population increased from approximately 2.8 million in 1940 to roughly 10.6 million by 2010, or a growth rate of nearly 400 %. For the most part, the region is characterized by low population density; however, the urban corridor that includes the Portland and Seattle metropolitan statistical areas (MSAs) was home to approximately 6 million of the 10.6 million residents in the region in 2010. Moreover, the region's primary urban corridor is susceptible to a number of prominent geophysical threats, including a spectrum of geologic, meteorological, climatological, and contextual hazards.

This research investigates the changes in the Pacific Northwest's exposure to the region's well-known Cascadia volcano threat and its resulting hazards. To what degree has the prevailing regional development morphologies of urban sprawl (Duany et al. 2000; Gillham 2002; Hall and Ashley 2008) and exurban growth (Theobald 2005; Greene and Pick 2013) increased the exposure to these hazards during the past 70 years? And, looking to the future, to what extent will predicted changes in development and the residential built-environment affect volcano-related hazards exposure during the remainder of the twenty-first century? We assess these questions by employing output from a fine-scale housing unit density model for historical, current, and future time periods (1940–2100) and, thereafter, use a threefold, downscaling analysis method on those data to appraise regional, proximal, and local hazard exposure perspectives. In quantifying historical and future changes in exposure, the research seeks to inform decision makers, emergency practitioners, and the public of the potential for future volcano disasters.

2 Cascadia hazards and volcanoes

2.1 Hazards

Volcanoes are openings or ruptures in the crust of the earth that allow lava, pyroclastics, and gasses to escape from a magma system below the surface. Violent volcanic eruptions can often lead to drastic changes on the surface of the earth. During a volcanic eruption, hazards such as lava flows, pyroclastic density currents (PDCs), lahars, landslides, tephra fallout, and ash clouds can result in potential casualties, built-environment loss, and disruptions in the natural ecosystem within hazard impact zones.

Lahars, which are saturated debris flows that originate on the volcano face, can travel at high rates of speed (>20 m s^{-1}), long distances (>25 km), and are considered to be one of the deadliest volcanic hazards (cf. Witham 2005). Eruptions may trigger one or more lahars directly by melting snow cover and ice or by ejecting water from a crater or nearby lake (USGS 2013a, b). Stratovolcanoes, which constitute the principal threatening volcano peaks in Cascadia, are often associated with lahars upon eruption due to their steep slopes, high elevations (more perennial snow cover), easily eroded rock, and tendency to erupt explosively. PDCs are mixtures of high-density, dry rock fragments and hot gases (>200 °C) that are erupted at extreme velocities (up to 1000 km h^{-1}) from a volcanic vent. Most PDCs comprise a basal flow of coarse rock fragments that traverses along the ground as well as a turbulent cloud of volcanic ash that may rise above the basal flow (Druitt 1998). This cloud can result in ash deposits over a large geographic area downwind from the volcano or PDC. Volcanic landslides or debris avalanches often contain large amounts of rock and soil that can travel more than 100 km from the landslide origin (USGS 2013a, b), moving at speeds of up to 80 m s^{-1}. Landslides often contain a mixture of dry or wet debris that may cause them to transform into a lahar during their lifecycle. An example of a devastating volcanic landslide occurred with the 18 May 1980 Mount St. Helens eruption in Cascadia where a 2.5-km^3-volume landslide reached speeds of 50–80 m s^{-1} and traversed up and over a 400-m tall ridge located 5 km from the volcano center (USGS 2013a, b). In general, volcanic landslides may lead to dramatic alteration of stream flows, drainage, and topography and can result in valleys, towns, or cities being buried in tens to hundreds of meters of rock, mud, and debris.

2.2 Geography

The US Pacific Northwest encompasses portions of the Cascadia volcanic arc, which contains over 20 (13 located in the USA) major volcanoes including stratovolcanoes, shield volcanoes, lava domes, and cinder cones (USGS 2013a). The Cascadia volcanoes are a result of subduction of the Juan de Fuca and Gorda Plates located 80 km off the Pacific coast. Eleven of the thirteen Cascadia volcanoes located in the USA have erupted at least once in the past four millennia, with seven of those erupting in the most recent two centuries (Dzurisin et al. 2008). Collectively, the volcanoes of the Cascade Range have resulted in over 100 eruptions in the past 1000 years with a majority of these eruptions being explosive (Dzurisin et al. 2008). Of major concern are "high- to very high-threat" volcanoes of Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Hood (USGS 2013a). These volcanoes are considered highest priority given their proximity to large population centers, explosive potential, and expected hazard production (e.g., lahars, PDCs, landslides).

Mount Baker has primarily erupted steam and particulate material from the central crater (Easterbrook 1975; Hildreth et al. 2003). However, as recently as 1975, columns of steam were seen rising from the summit of Mount Baker from the Puget lowland (Easterbrook 1975). Shortly thereafter, melting of the volcano glaciers began to take place. This observation led researchers (Frank et al. 1977) to believe that the volcano was beginning to "heat up" for the first time in 120 years and provided Mount Baker's eruption history, the potential for ash, mudflows, floods, and lava flows existed.

Glacier Peak is a small stratovolcano with a history of producing tephra fall and lahars (Mastin and Waitt 2005). Approximately 13,000 years ago, Glacier Peak produced lahars from pyroclastic flows mixed with glacial ice, snow, rocks, and mud (Mastin and Waitt 2005). One particular lahar traveled nearly 97 km and deposited up to 2.1 m of sediment.

More recent activity included lahars that have traveled to the Pacific Ocean twice in the last 6000 years (Mastin and Waitt 2005).

Of the high-risk volcanoes located in the Cascadia Range, Mount St. Helens and Mount Rainier are of foremost concern (Wood and Soulard 2009). Rainier has produced lahars that reached the Puget Sound lowlands on average once every 500–1000 years or at least seven times, historically (Wood and Soulard 2009). Previous research has suggested that there is a 10 % chance of a lahar affecting populations and developed landscapes within the average human life span (Driedger and Scott 2008; Wood and Soulard 2009). Rainier has most commonly produced lahars due to the cloak of snow and ice covering the upper volcano flanks (USGS 2013a). The most notable of these lahars is the Osceola Mudflow, which occurred approximately 5600 years ago (USGS 2013a). A 1.8-km-wide crater opened on the northeast flank of the volcano—similar to the 1980 eruption of St. Helens—and resulted in a lahar that covered an area of 550 km^2, including the Puget Sound lowlands (USGS 2013a). The Osceola Mudflow reached locations as far as Seattle suburban communities of Kent and Commencement Bay (USGS 2013a). Current communities such as Orting, Buckley, Sumner, Puyallup, Enumclaw, and Auburn have since been built atop this mudflow deposit (USGS 2013a). More recent Rainier lahars and mudflows (i.e., Round Pass, National, Electron) have also affected locations within the Puget Sound lowlands by traveling at least 100 km toward the Pacific Ocean (USGS 2013a).

Mount St. Helens dramatically illustrated its ability to produce an explosive eruption on May 18, 1980, when a moderate (5 on the Richter scale) earthquake triggered the collapse of the north face of the volcano. This resulted in a pyroclastic flow that covered 600 km^2 and the injection of more than 1.5 million metric tons of sulfur dioxide into the atmosphere (Gerlach and McGee 1994). The resulting pyroclastic flow and lahar traveled 27 km where it then released into the Columbia River. Mount St. Helens has indicated the redevelopment of a lava dome on the south side of the crater and produced ash and steam clouds visible from the Seattle MSA (USGS 2014).

For the past 500,000 years, Mount Hood has been active, often producing lava flows, pyroclastic flows, lava domes, and lahars (USGS 2012). Hood has previously produced lahars that have buried the valley floors within the Sandy and Hood river drainages (USGS 2012). Located 80 km from downtown Portland, Hood remains a concern given its eruptive history.

3 Data and methodology

A number of studies have investigated the growth in populations and affiliated built-environments, defining spatial metrics of development types (i.e., urban, suburban, and exurban, as well as sprawl) and assessing how those morphologies interact with the natural environment (Alig and Healy 1987; Ewing 1994; Benfield et al. 1999; Katz and Liu 2000; Waldie 2000; Ewing et al. 2005; Theobald 2005; Bhatta et al. 2010). The measurement of development is typically tied to the amount of people throughout a landscape, as well as their place of residence, or housing unit (HU). Previous literature examining changes in hazard exposure has primarily relied on decennial censuses as the sole measure of accurate historical population and HU counts in the USA (Wood and Soulard 2009; Ashley et al. 2014). However, the geographic units of aggregation vary from one census to the next, restricting spatiotemporal comparison and quantification of hazard exposure and vulnerability change (Ashley et al. 2014). Further, relatively fine-scale census enumerations are not available over extended historical periods (e.g., block-level resolution is solely available for the 1990, 2000, and 2010). To address these variable spatial unit concerns, previous studies (Deichmann et al. 2001; Schlossberg 2003; Balk et al. 2005; Ashley et al. 2014) have employed areal weighting or proportional allocation, which is a method advocated by the Socioeconomic Data and Applications Center (SEDAC) to transform variable census enumerations onto uniform grid cells. While this methodology does control for variable spatial units of exposure data, it does not address the issue of coarse spatial and temporal resolution.

We eliminate the spatial unit variable problem and data coarseness found in previous research by employing fine-scale housing unit density output derived from the Spatially Explicit Regional Growth Model (SERGoM; Theobald 2005). This spatial allocation model was originally developed to investigate historical and contemporary urban-to-rural land-use transformation and associated ecosystem fragmentation (Theobald 2001, 2003, 2005). Historical information on the distribution of HUs in the model was derived from the Census' Summary File 1 and road density data, with model accuracy measured using a hindcast technique (cf. Theobald 2005). Cross-validation between the US Census Bureau's historical population and HU data results confirmed that the SERGoM hindcasts performed well for all land-use classifications (Theobald 2005; US EPA 2009).

Forecasts of HU density in the SERGoM were initially based on the relationship between historical growth patterns and accessibility (e.g., roads) to urban and protected lands (Theobald 2005), while later versions of the SERGoM incorporated Intergovernmental Panel on Climate Change (IPCC) expectations of future climate and societal changes outlined in the Special Report Emission Scenarios (SRES; Bierwagen et al. 2010; IPCC 2012, 2014). Specifically, the EPA's Integrated Climate and Land Use Scenarios (ICLUS) research group integrated the SRES A1, A2, B1, and B2 emission forecasts with the SERGoM model to estimate future demographic change (Bierwagen et al. 2010; Fig. 1). The SERGoM was chosen by the ICLUS group because it is the only land-use change model that allocates housing density from rural to urban across the conterminous USA (EPA 2009).

Alternative modeling approaches such as the National Resources Conservation Service's (NRCS) Natural Resource Inventory do not provide spatially explicit forecasts of land-use change (Nowak and Walton 2005); those modeling approaches that do utilize spatially explicit methods simply do not exist in an easily available format across the conterminous USA (e.g., Landis and Zhang 1998; Irwin and Bockstael 2002; Waddell 2002; Jantz et al. 2003; EPA 2009). Additionally, cellular automata modeling using the Slope, Land use, Urban area, Transportation, Hillside area (SLEUTH) model revealed no

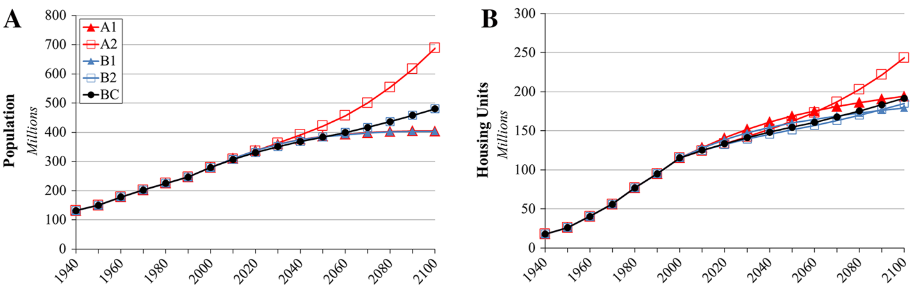

Fig. 1 Conterminous US historic and forecast **a** population and **b** housing units from 1940 to 2100 by SRES A1, A2, B1, B2, and BC

major differences between the SERGoM and SLEUTH after the SERGoM was aggregated to match the much coarser spatial resolution of the SLEUTH model (e.g., Batty 1997; Theobald and Hobbs 1998; EPA 2009). Although some European countries do provide land-use models at national-extent, the data associated with these models cannot be applied to the large spatial extent of the conterminous USA because of computational limitations and complexities (Verburg et al. 2002, 2006; EPA 2009). An advantage of employing the SERGoM in conjunction with the ICLUS SRES is that the SERGoM forecasts allow for the establishment of statistical relationships among neighboring grid cells, population growth rates, and transportation infrastructure (Theobald 2005; EPA 2009). The greatest benefit of coupling the SERGoM with the SRES storylines is the technical advantage of producing fewer discrete differences across artificial analytical boundaries that would be formed by integrating individual model runs into complete conterminous US coverage (EPA 2009).

The modified US A1 storyline illustrates rapid economic development, low population growth, and global integration (US EPA 2009). The A2 scenario is the population growth and housing density projection scenario that is concentrated on consistent economic growth with a regional focus rather than environmental sustainability. The fertility rates and

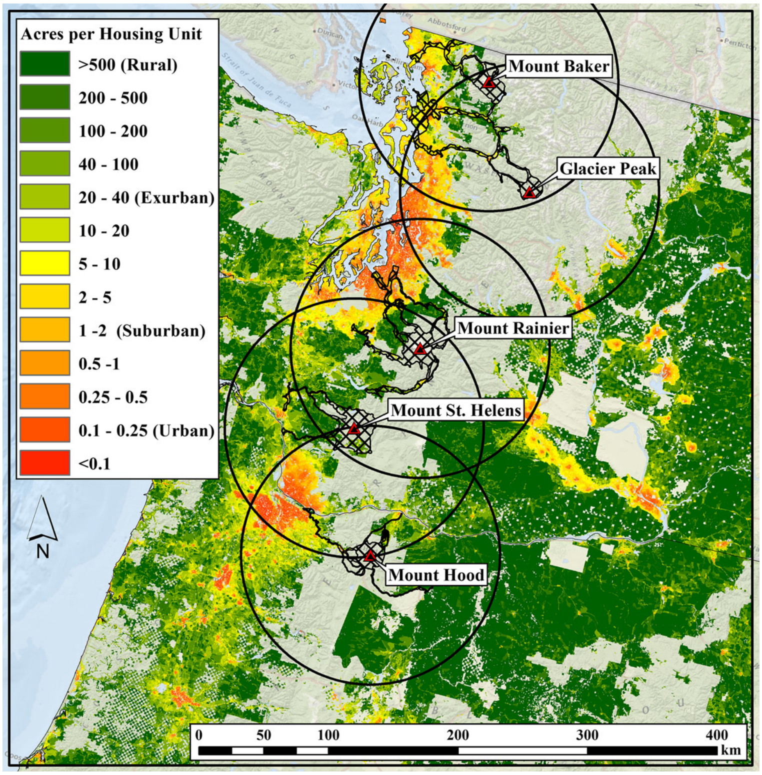

Fig. 2 Map of the study region and resolutions with the underlying A2 scenario housing unit density forecast at 2100. The *black outline box* represents the regional study area; the individual 100-km-radius buffers comprise the proximal study areas; and the USGA volcano hazard zones are shown in *gray with a black outline* (cf. Fig. 3). The housing unit density classification scheme (urban, suburban, exurban, and rural) is determined by the same thresholds employed in EPA (2009)

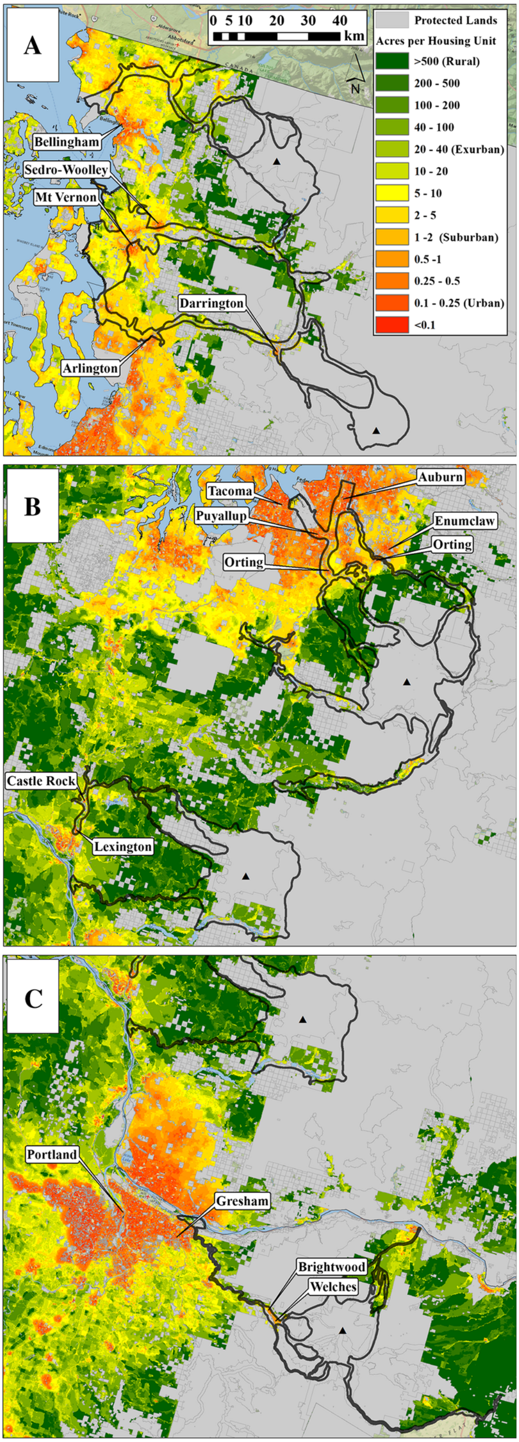

Fig. 3 Local volcano hazard zones including: **a** Mount Baker and Glacier Peak; **b** Mount Rainier and Mount St. Helens; and **c** Mount St. Helens and Mount Hood. Base layer same as Fig. 2 with protected Federal, State, and local lands illustrated as well. Cities and towns discussed in the text are indicated

domestic migration are assumed to be higher in the A2 scenario compared to all other SRES scenarios because of the continued focus on economic development and global trends. High domestic migration leads to the drawing of population from rural areas that contribute to a slight decrease in exurban densities and increases in suburban and urban densities (Bierwagen et al. 2010). The B1 scenario closely mirrors the A1 storyline but contains a greater emphasis on environment and sustainable economic growth at the regional level. Fertility rates in the B1 scenario are considered low due to higher incomes and greater regional economic growth. International migration is expected to be relatively higher because of the focus on economic developments within a less-restricted global economy. The B2 storyline comprises a regionally oriented landscape with moderate population growth with a focus on local solutions to environment and economic issues (US EPA 2009). This scenario is the most environmentally driven compared to all other SRES storylines. The ICLUS provides an additional growth projection, a base case (BC), where all model parameters (e.g., county migration, percentage water area for a county, county growth rate) were set to "medium." HU output from the SERGoM is at 100-m resolution for the conterminous USA, with historical data available from 1940 to 2000 and projected SRES and baseline scenarios from 2010 to 2100. It is important to note that the goal of this research is not to predict what will happen, but to project a range of likely future changes in land use that may have consequences associated with hazard exposure.

Spatiotemporal analyses of volcanic hazard exposure change are quantified by using the HU density as the primary exposure metric for three different geographic scales: regional, proximal, and local. While the number of people affected in a volcano disaster may vary depending on the situation (e.g., time of day, date, warning lead time), estimations of HUs and people impacted should be relatively strong markers for assessing spatiotemporal changes in the regional, proximal, and local hazard zone volcano disaster landscapes. The regional domain is defined as the western two-thirds of Washington and Oregon, which contains cities such as Seattle, WA, Tacoma, WA, and Portland, OR, as well as high-threat volcanoes Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Hood (Fig. 2). To examine further the historical and future volcanic hazard exposure for the high-threat volcanoes, more refined proximal and local hazard analyses are conducted using a fixed distance buffer of 100 km from the center of the volcano of interest as well as historical georeferenced volcanic hazard (lava, debris, lahar, and mud flows) zone maps (Figs. 2, 3). The proximal buffer distance was chosen to represent the potential distance a landslide, lahar, and/or debris flow can travel during an eruption. Although volcanic hazards such as lahars have the propensity to flow in areas where previous lahars have occurred, the proximal analysis captures areas that may be impacted by a debris avalanche if a flank of a volcano were to collapse (e.g., 1980 Mount St. Helens and 1840 Mt. Baker). The proximal analysis also encapsulates areas that may be affected if a lahar or debris flow were to occur and reservoir dams downstream failed as a result (USGS 2013a, b). The local hazard zones were determined by the USGS-defined historical impact areas associated with previous volcano eruptions. These local hazard zone analyses capture the enhanced lahar, debris/pyroclastic flow, and flood risk since volcano hazard events have a propensity to affect the same drainages (USGS 2013a, b).

4 Results

The results of this research are presented in three parts. First, we discuss the "historical" (1940–2000) and "future" (2010–2100) conterminous US population and HU growth

Table 1 Conterminous US absolute (×1,000,000 units) and percentage change in population and housing units

	Population (×1,000,000)				Housing units (×1,000,000)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Absolute change								
A1	147.41	106.3	17.7	271.5	97.5	53.5	25.4	176.4
A2	147.41	142.1	266.8	556.3	97.5	46.7	81.4	225.6
B1	147.41	105.4	17.4	270.2	97.5	44.7	18.9	161.1
B2	147.41	104.3	96.3	348.0	97.5	36.1	33.7	167.3
BC	147.41	104.3	96.3	348.0	97.5	39.3	37.2	174.0
	Population (%)				Housing units (%)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Percentage change								
A1	111.5	38.0	4.6	205.4	549.7	46.5	15.1	994.8
A2	111.5	50.8	63.3	420.9	549.7	40.5	50.3	1272.3
B1	111.5	37.7	4.5	204.4	549.7	38.8	11.8	908.8
B2	111.5	37.3	25.1	263.3	549.7	31.3	22.3	943.3
BC	111.5	37.3	25.1	263.3	549.7	34.1	24.1	981.2

projections. Second, spatiotemporal changes in Cascadia volcanic hazard exposure are assessed under regional, proximal, and local hazard spatial scales to determine how the Northwest US volcano disaster landscape has evolved through time and across geographic space. In the last section, we examine how rural (>40 acres per HU), exurban (2–40 acres per HU), suburban (0.25–2 acres per HU), and urban (<0.25 acres per HU) land-use patterns influence volcanic disaster potential at the regional, proximal, and local hazard spatial scales.

4.1 Changes in conterminous US population and housing units

Based on SERGoM output, the conterminous US total population increased from 132 to 280 million people during the 60-year time period from 1940 to 2000. This growth constitutes a 156 % change in total number of persons. Throughout this same period, HU counts amplified from 18 million to 115 million, which is a 540 % increase (Table 1; Fig. 1).

For future SRES projection storylines (Table 1; Fig. 1), the A2 scenario contains the greatest overall inflation in conterminous US population, with a 146 % increase from 2000 to 2100. The main drivers of this amplification in total population are the high fertility rates and net international migration predicted in the A2 scenario (EPA 2009). Because of their projected low fertility, the A1 and B1 storylines represent the lowest percentage growth in population from 2000 to 2100, or a 44 % increase. The A1 and B1 population projections for the USA illustrate similar growth trajectories. Regional declines in fertility rates are controlled by rapid social and educational development for women in the B1 storyline, whereas economic development is primarily responsible for the declining A1 scenario fertility rates (EPA 2009). The B2 and BC storylines represent similar population growth trajectories due to their "medium" projections in fertility and international migration (EPA 2009). The major difference between the B2 and BC scenarios are the migration flow rates. The BC scenario is epitomized by a "middle-of-the-road" flow, while the B2 storyline represents low domestic migration (EPA 2009). Although not easily discernible at the conterminous US spatial scale, this difference in B2 and BC international migration results in B2 suburban and urban areas generally growing faster than rural areas in the BC scenario.

The conterminous US ICLUS HU trajectories are more variable and diverse than the ICLUS population forecasts from 2000 to 2100 (Fig. 1b). For all SRES storylines, future HU counts are expected to increase between 60 and 111 % from 2000 to 2100. The A2 scenario exemplifies the highest increase in the total number of HUs from 2000 to 2100 because of the ICLUS greater projected household size (+15 %) and greater weight placed on longer travel times from the central business districts in order to encourage development in more suburban areas (Table 1) (EPA 2009). The B2 storyline represents the least amount of HU growth due to a greater weight placed on shorter travel times to the central business districts that encourages infill and a more compact growth pattern and no change in household size from historical records (Table 1) (EPA 2009).

Although the A2 scenario encompasses the greatest growth in HUs by 2100, the A1 and B1 SRES contain the greatest HU growth throughout the first half of the twenty-first century (Fig. 1b). The A2's total number of HUs is forecast to surpass the B1's projections by 2050, while the A1 scenario will be overtaken by the A2 scenario in 2070. The primary cause of these trajectory differences is the varying population growth rates for each SRES storyline. In general, new job opportunities, improved infrastructure, and increased wealth result in the rapid urban and suburban growth from 1940 to 2100 (Brown et al. 2005;

Table 2 As in Table 1, except for the volcano regional study area

	Population (×1,000,000)				Housing units (×1,000,000)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Absolute change								
A1	5.3	2.1	0.6	9.0	3.1	1.6	0.8	5.5
A2	5.3	3.4	6.0	14.6	3.1	1.0	1.8	5.9
B1	5.3	4.2	1.2	10.6	3.1	1.8	0.9	5.7
B2	5.3	3.0	2.6	10.9	3.1	1.0	0.9	5.0
BC	5.3	2.6	2.1	10.0	3.1	1.0	0.8	4.9
	Population (%)				Housing Units (%)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Percentage change								
A1	159.8	25.2	4.7	274.3	698.0	46.0	15.2	1242.0
A2	159.8	39.4	50.5	444.9	698.0	28.8	38.5	1335.8
B1	159.8	48.7	9.4	322.4	698.0	49.9	19.7	1300.1
B2	159.8	35.5	22.4	330.9	698.0	29.6	19.7	1137.2
BC	159.8	30.8	19.0	304.3	698.0	27.8	18.0	1103.2

Hansen et al. 2014), as well as greater disaster potentiality when hazards interact with this expanding population.

4.2 Regional analysis

From 1940 to 2000, the regional study area experienced a 160 % increase in total population, growing from 3.2 to 8.5 million people (Table 2; Fig. 4). For the historical period of record, the regional study area's number of HUs amplified from 441,000 to 3.5 million, or a 698 % increase over 60 years. Similar to the conterminous US future scenario projections from 2000 to 2100, the A2 storyline forecasts the greatest overall growth in population and HUs with a 110 % increase in the total number of people and 80 % amplification in HU counts. This sizeable intensification is largely due to the effects of high fertility rates and strong international migration to population centers (i.e., Portland, OR and Seattle–Tacoma, WA) that contain greater than 75 % (5.6 Million people) of the total persons living in the regional study area based on the 2010 US Census. However, unlike the conterminous US future population growth projections, the B2 and B1 scenarios yield the second and third greatest increases in population totals at 66 and 63 %, respectively, due to the region's propensity to focus on sustainable and eco-friendly development (Svoboda 2008). Analogous to the conterminous US SRES forecasts, the B1 scenario yields rapid population growth throughout the first half of the twenty-first century, surpassing all other SRES storyline estimations until 2060 when the A2 scenario is predicted to overtake the B1 storyline. The leveling of the B1 and A1 scenario population trajectories is expected given the ICLUS model forecast decline in B1 and A1 growth rates through the twenty-first century (EPA 2009).

While the A2 storyline does yield the greatest growth in the regional study area HU counts for the entire future study period, the A1 and B1 scenarios illustrate greater HU totals during much of the 100-year period (Fig. 4b). From 2000 to 2050, the B1 SRES has a 50 % growth in HUs while the A1 scenario has a 46 % escalation. However, the B1 and A1 storylines only forecast another 15–19 % increase from 2050 to 2100, while the A2 SRES estimates a 39 % rise in total HUs throughout this same time period. These differences in HU SRES trajectories are a result of the changes in population growth rates inherent in each storyline. The rapid A1 and B1 HU growth throughout the first 50 years of the twenty-first century can also be attributed to the focus on a globally integrated world where there is rapid economic convergence between regions (EPA 2009). The A2 storyline emphasizes strong economic growth with a regional focus where the economic

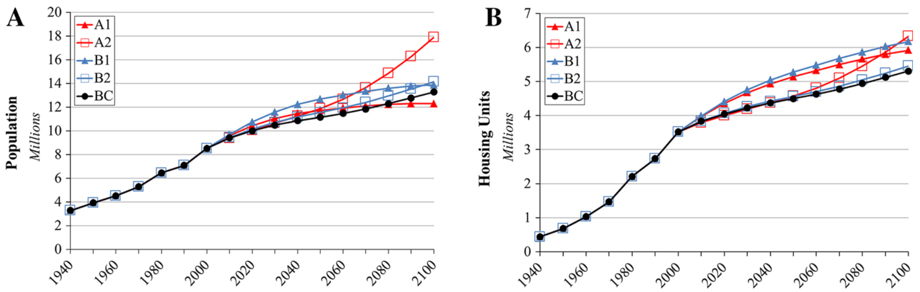

Fig. 4 Northwest US regional study area historic and forecast **a** population and **b** housing units from 1940 to 2100 by SRES A1, A2, B1, B2, and BC

convergence between regions occurs much slower. In the latter half of the century, the combination of increasing population growth rates, high fertility, and amplified domestic migration allows the A2 scenario to yield final HU counts greater than those of the other SRES storylines. The B2 and BC storylines encompass the least amount of regional HU growth (50–55 %) throughout the future period from 2000 to 2100, partially because of their medium projected fertility and low domestic migration (EPA 2009). Another factor for the rapid growth in the Northwest US region is that the historical international immigration data employed in the ICLUS demographic model is relatively high for the Pacific Northwest. Therefore, the A1 and B1 growth scenarios allocate a greater number of international immigrants into this region.

For the entire 160-year period of analysis, the regional study area's percentage increases in population range from 274 to 445 %, with the number of HUs growing between 1103 and 1336 %. Consequently, the Northwest US regional study area could contain five times more people and 14 times the HUs on average by the end of the twenty-first century in comparison with the mid part of the twentieth century. Although the volcanic hazard risk is not the same for all persons and communities within the Northwest region, if the area were

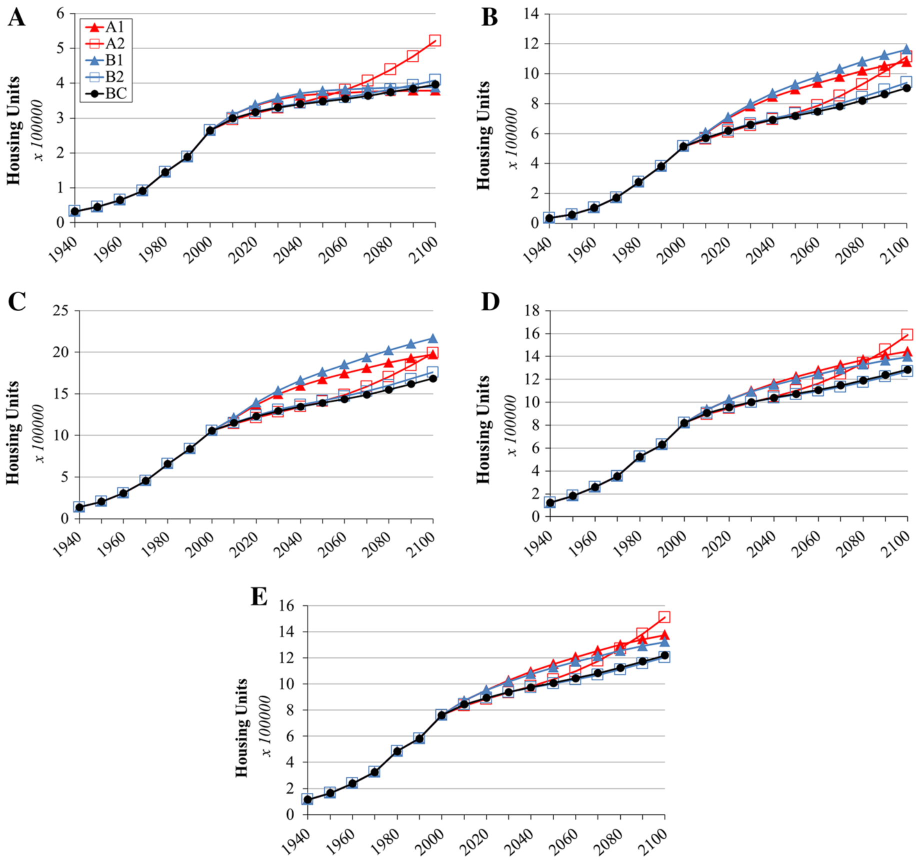

Fig. 5 Volcano proximal study areas historic and forecast housing units from 1940 to 2100 by SRES A1, A2, B1, B2, and BC. **a** Mount Baker; **b** Glacier Peak; **c** Mount Rainier; **d** Mount St. Helens; and **e** Mount Hood

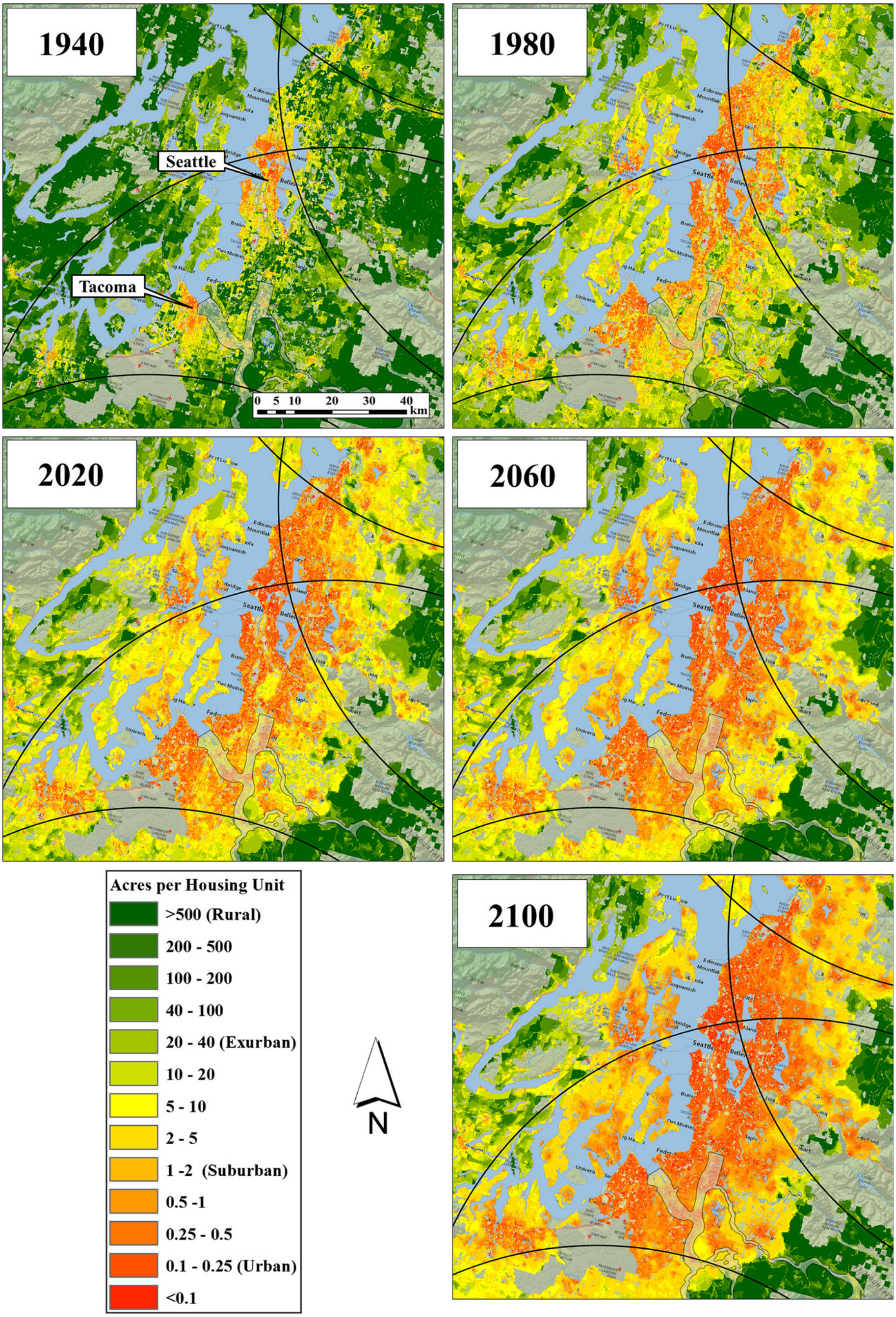

Fig. 6 Seattle, WA metropolitan area housing unit growth from 1940 to 2100 by the SRES A2. The Mount Rainier volcano hazard zone is illustrated along with portions of the Glacier Peak, Mount Rainier, and Mount St. Helens proximal volcano hazard zones

Table 3 Absolute change (×10,000 units) in population and housing units for the volcano proximal areas

	Population (×10,000)				Housing units (×10,000)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Mount Baker								
A1	40.1	20.3	−5.8	54.5	23.3	10.5	0.9	34.6
A2	40.1	29.7	9.7	123.3	23.3	9.6	2.8	48.9
B1	40.1	26.7	−3.8	63.1	23.3	11.3	1.0	35.6
B2	40.1	24.9	1.7	82.0	23.3	8.7	0.5	37.6
BC	40.1	22.1	1.4	75.1	23.3	8.3	0.4	36.4
Glacier Peak								
A1	98.6	80.1	19.9	198.6	47.8	38.1	18.5	104.5
A2	98.6	67.4	123.5	289.5	47.8	22.4	37.8	108.0
B1	98.6	99.0	38.1	235.7	47.8	41.5	23.4	112.8
B2	98.6	61.0	58.6	218.3	47.8	21.8	21.0	90.6
BC	98.6	54.1	48.2	201.0	47.8	20.6	18.6	87.1
Mount Rainier								
A1	154.8	126.3	27.2	308.3	92.2	61.7	29.9	183.8
A2	154.8	110.3	195.8	460.8	92.2	35.2	58.0	185.3
B1	154.8	167.4	63.1	385.3	92.2	70.4	40.4	203.1
B2	154.8	103.3	96.6	354.7	92.2	36.1	34.0	162.3
BC	154.8	88.5	76.6	319.8	92.2	33.2	29.4	154.8
Mount St. Helens								
A1	106.7	80.4	20.7	207.8	69.7	40.2	22.2	132.0
A2	106.7	52.6	78.3	237.6	69.7	28.0	48.7	146.4
B1	106.7	89.7	25.1	221.5	69.7	38.0	19.6	127.2
B2	106.7	71.7	59.0	237.3	69.7	24.6	20.3	114.6
BC	106.7	67.3	55.7	229.7	69.7	25.2	21.3	116.2

Table 3 continued

	Population (×10,000)				Housing units (×10,000)			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Mount Hood								
A1	100.2	78.4	22.6	201.2	64.9	39.0	22.4	126.2
A2	100.2	84.5	157.8	342.4	64.9	27.3	47.5	139.7
B1	100.2	85.9	26.4	212.5	64.9	36.3	19.7	120.8
B2	100.2	69.6	58.1	227.9	64.9	24.1	20.1	109.1
BC	100.2	65.5	55.0	220.6	64.9	24.6	21.1	110.6

to experience a significant volcano eruption, much of the region would suffer from negative environmental, health, and economic consequences (Baxter et al. 1981; Hunn and Norton 1984; Hansen et al. 2014). Even if volcano risk is held constant, disaster potentiality has dramatically increased and will continue to surge, due to the escalation of people and their residential built-environments in proximity to known volcano hazards.

4.3 Proximal analyses

Comparing all volcano proximal regions from 1940 to 2000, the Mount Rainier proximal hazard area experienced the greatest expansion in number of persons and HUs, amplifying from approximately 260,000 to 1.2 million people and growing from 137,000 to 1 million HUs (Fig. 5). This rapid development is attributed to the Mount Rainier proximal zone containing large portions of the Seattle–Tacoma MSA. These higher-density locations often grow at much faster rates compared to less dense communities because of their concentration of job centers, wealth, improved transportation, and employment opportunities (Census Bureau 2012; Hansen et al. 2014). The Mount St. Helens and Mount Hood proximal domains have the second and third greatest population and HU total growth, respectively, from 1940 to 2000. Again, this is largely due to both the Mount St. Helens and Mount Hood proximal areas encompassing portions of the Portland-Vancouver-Hillsboro, OR-WA MSA where the bulk of the population and development tend to cluster within the region. While the Mount Rainier, Mount St. Helens, and Mount Hood proximal buffer areas contain the greatest total increase in people and HUs throughout the historical period, the Glacier Peak proximal study area contains the largest percentage increase in population and HU counts with 155 and 1376 %, respectively. The rapid development highlighted in the Glacier Peak proximal area is a result of an economic boom in the mid-1940s led by The Boeing Company and their involvement in WWII (Sell 2011). The need for factory workers and infrastructure enabled the northern and eastern portions of the Seattle–Tacoma MSA to quickly expand and develop throughout much of the historical period.

The Mount Rainier proximal area had the greatest overall volcanic hazard exposure and risk within the entire Northwest region due to the area's propensity to experience lahars and mudflows near locations with relatively high population density (Fig. 6). The Mount Rainier proximal area is also forecast to contain the greatest population and HUs by 2100, increasing to as much as 5.6 million people and 2.2 million HUs. While the A2 scenario had the highest increase in future population for the Mount Rainier proximal area, the maximum HU growth scenario is featured in the B1 SRES where an additional 1.1 million HUs are expected to be added from 2000 to 2100 (Table 3). Although 78 % of the Glacier Peak proximal area is designated as protected Federal, State, or local lands, it still forecast to undergo the greatest percentage growth in population and HUs from 2000 to 2100 compared to all other volcano proximal hazard areas. The Glacier Peak volcano proximal area is able to overcome the lack of developable, non-protected lands because it contains higher-density locations such as northern Seattle, Everett, and Mount Vernon, which are urban areas that are forecast to continue rapid growth through much of the twenty-first century. The A2 SRES estimates a 153 % increase in population, and the B1 storyline predicts a 127 % increase in total number of HUs from 2000 to 2100.

Overall, the greatest percentage change in population during the 160-year period is found in the Glacier Peak proximal area where the A2 scenario forecasts a 1117 % amplification. Although the Glacier Peak proximal area A2 storyline indicates the greatest growth in population from 1940 to 2100, the Glacier Peak proximal buffer B1 scenario

Table 4 Absolute change in population and housing units for the local hazard study regions

	Population				Housing units			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Mount Baker								
A1	18,521	13,840	−5544	26,817	15,913	7270	53	23,236
A2	18,521	21,557	7558	81,299	15,913	6925	2201	35,274
B1	18,521	22,956	−1773	39,704	15,913	9703	1292	26,907
B2	18,521	20,953	1271	56,080	15,913	7385	378	29,084
BC	18,521	16,593	910	44,888	15,913	6223	225	25,819
Glacier Peak								
A1	18,070	20,383	−4988	33,465	15,238	10,076	510	25,823
A2	18,070	27,583	54,098	99,751	15,238	9301	16,872	41,410
B1	18,070	27,865	−1314	44,621	15,238	11,735	1575	28,547
B2	18,070	24,668	20,288	63,027	15,238	8,889	7192	31,318
BC	18,070	21,302	14,162	53,535	15,238	8140	5426	28,803
Mount Rainier								
A1	65,180	60,752	8053	133,986	37,418	29,167	11,045	77,630
A2	65,180	55,880	98,933	219,994	37,418	18,570	30,112	86,100
B1	65,180	78,049	19,431	162,660	37,418	32,779	13,929	84,126
B2	65,180	51,972	43,866	161,018	37,418	18,618	15,532	71,567
BC	65,180	44,931	36,575	146,687	37,418	17,113	14,101	68,631
Mount St. Helens								
A1	5808	925	−919	5813	3437	646	17	4100
A2	5808	1760	1006	8574	3437	408	10	3855
B1	5808	3593	−586	8814	3437	1525	123	5086
B2	5808	2622	1095	9524	3437	861	315	4612
BC	5808	1474	109	7391	3437	503	6	3947

Table 4 continued

	Population				Housing units			
	1940–2000	2000–2050	2050–2100	1940–2100	1940–2000	2000–2050	2050–2100	1940–2100
Mount Hood								
A1	4690	976	−979	4687	3351	674	0	4025
A2	4690	2735	6513	13,939	3351	776	1920	6047
B1	4690	2220	−789	6121	3351	956	0	4307
B2	4690	3011	1202	8903	3351	1010	350	4711
BC	4690	2183	152	7025	3351	786	20	4158

represents the greatest percentage growth in HUs throughout the period with a 3245 % increase. The Mount Rainier proximal area yields the greatest total increases in population and HUs with 4.6 million people and 2 million HUs during the 160-year period. These results suggest that although the Mount Rainier proximal study area yields the greatest increases in 2100 population and HU totals, the Glacier Peak proximal study area population and HU counts are increasing at a greater rate.

4.4 Local hazard zone analyses

All local hazard zones experienced population and HU growth greater than 40 % from 1940 to 2000 (Table 4; Fig. 7). For the historical period, the Mount Rainier local hazard zone had the greatest overall increase in total population and HUs, amplifying from 38,000 to 103,000 people and 5100 to 42,500 HUs. Because the lack of population centers located within the hazard zone boundaries, as well as the high percentage of protected lands, the

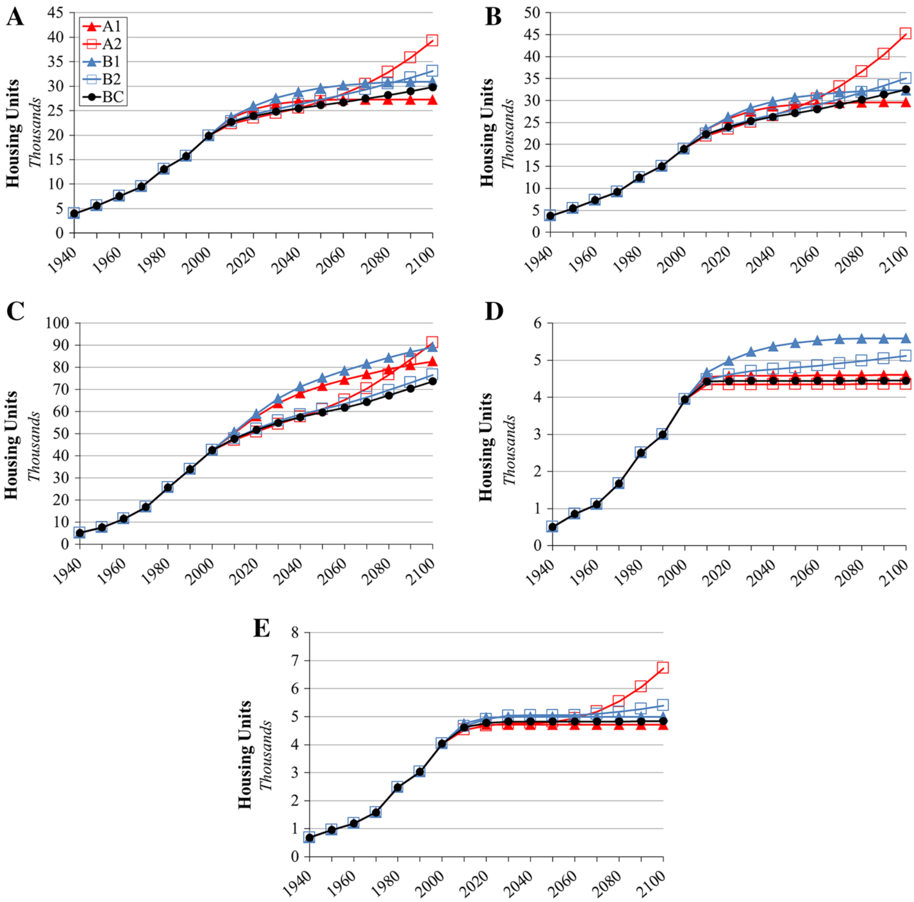

Fig. 7 Local volcano hazard study areas historic and forecast housing units from 1940 to 2100 by SRES A1, A2, B1, B2, and BC. **a** Mount Baker; **b** Glacier Peak; **c** Mount Rainier; **d** Mount St. Helens; and **e** Mount Hood

Mount St. Helens and Mount Hood hazard zones illustrate the lowest overall growth in population and HUs throughout the historical time period. However, from 1940 to 2000, the Mount St. Helens and Mount Hood local hazard zones experienced the greatest percentage increases in population where they amplified 155 and 92 %, respectively. This disparity in absolute and percentage increases in population and HUs for the Mount St. Helens and Mount Hood local hazard zones is attributed to the overall low amount of developable land and fewer total number of people living within the Mount St. Helens and Mount Hood local hazard zones.

From 2000 to 2100, the Mount Rainier local hazard zone is forecast to experience the greatest overall increase in population, increasing by approximately 155,000 persons based on the A2 storyline. This is primarily due to the local hazard zone boundary intersecting portions of highly urban and suburban developed communities such as Puyallup, Sumner, Auburn, and Orting. However, the greatest percentage change in population throughout the future period is the Glacier Peak local hazard zone under an A2 scenario, which is expected to undergo a 177 % increase in total number of people (Table 4; Fig. 7). Similarly, the Mount Rainier and Glacier Peak local hazard zones are forecast to experience the greatest overall growth in HUs based on the A2 scenario compared to all other local hazard zones. The Mount Rainier local hazard zone will tally an additional 49,000 HUs, while the Glacier Peak local hazard zone will experience a 137 % increase in the total number of HUs.

Throughout the entire 160-year period of analysis, the Mount Rainier local hazard zone is predicted to undergo the greatest change in total number of persons and HUs, adding an additional 220,000 people and 86,000 HUs based on the A2 storyline. The local hazard zone associated with Mount Rainier is also estimated to experience the greatest percentage increase in population and HUs from 1940 to 2100. Based on the A2 scenario, the Rainier's hazard zone during the study period will experience a 579 % increase in population and a 1689 % growth in the total number of HUs (Table 4; Fig. 6). The primary cause of the high total and percentage growth in exposure metrics is the inclusion of urban, suburban, and exurban communities—such as the Tacoma, Puyallup, Auburn, Buckley, and Enumclaw—in the local hazard zone (Fig. 6).

4.5 Land-use change and community analyses

To assess the development exposure change across our study areas, we employed the EPA (2009) ICLUS land-use classification on the 100-m grid cells and, thereafter, examined changes temporally. Changes in land-use area can be derived from increases or decreases

Table 5 Number of 0.01 km^2 grid cells by worst-case (i.e., greatest net change in HUs) SRES, percentage of total area, and percentage change for each land-use type in the regional study area from 1940 to 2100

Area	Land-use type	Count		% of total area km^2		% change 1940–2100
		1940	2100	1940	2100	
Regional (A2)	Rural	13,519,140	10,834,936	96.45	77.26	−19.85
	Exurban	442,122	2,378,460	3.15	16.96	437.96
	Suburban	49,758	653,258	0.35	4.66	1,212.87
	Urban	6,095	157,783	0.04	1.13	2,488.73

The worst-case SRES is indicated parenthetically in the total number of classified grid cells. In addition to historical land use from 1940 to 2000, all study areas (i.e., regional, proximal, and local hazard) are characterized by their worst-case future SRES storylines since these scenarios yield the greatest future increases in total HUs and, therefore, hazard exposure potentiality from 2000 to 2100. From 1940 to 2100, the regional study area is forecast to lose as much as 20 % of its rural land under an A2 scenario (Table 5). Regional classified urban land area is expected to increase from 0.04 to 1.13 % throughout the 160-year period. This growth in urban land use constitutes a 2489 % increase from 1940 to 2100. By 2100, rural land use represents 77 % of the total developed land area within the region, while exurban, suburban and urban land-use classifications comprise 17, 5, and 1 % of the total regional area, respectively. Although only 6 % of the regional area is classified as urban or suburban land use by 2100, much of this change is concentrated in the Tacoma–Seattle–Everett MSA, Portland-Vancouver-Hillsboro MSA, Yakima River Valley, and Columbia River Valley.

All volcano proximal areas are expected to experience greater than 22 % reductions in rural land from 1940 to 2100. The Mount Baker proximal study area is projected to lose the greatest percentage of rural land from 1940 to 2100 with an areal reduction of 69 %, whereas the Glacier Peak proximal buffer is forecast to experience a 16,609 % increase in urban land use during the same period (Table 6). The Mount Baker proximal area is the only volcano proximal zone that contains a majority (57 %) of its land use in the exurban classification by 2100. While all other volcano proximity regions have their greatest

Table 6 As in Table 5, except for volcano proximal areas

Area	Land-use type	Count		% of total area km^2		% Change 1940–2100
		1940	2100	1940	2100	
Baker (A2)	Rural	491,875	151,784	90.12	27.69	−69.14
	Exurban	50,191	312,358	9.20	56.98	522.34
	Suburban	3401	76,858	0.62	14.02	2159.86
	Urban	318	7176	0.06	1.31	2156.60
Glacier Peak (B1)	Rural	660,290	339,542	91.16	46.85	−48.58
	Exurban	59,646	247,455	8.23	34.15	314.87
	Suburban	4210	102,446	0.58	14.14	2333.40
	Urban	211	35,256	0.03	4.86	16,609.00
Rainier (B1)	Rural	1,386,282	897,671	91.65	59.30	−35.25
	Exurban	109,158	385,511	7.22	25.47	253.17
	Suburban	14,898	161,416	0.98	10.66	983.47
	Urban	2325	69,161	0.15	4.57	2874.67
St. Helens (A2)	Rural	27,255	20,445	94.11	64.52	−31.43
	Exurban	1025	7192	5.05	25.51	405.81
	Suburban	75	655	0.72	7.24	905.19
	Urban	0	62	0.12	2.73	2169.79
Hood (A2)	Rural	9907	5298	94.91	73.15	−22.93
	Exurban	2150	5333	4.31	17.56	307.02
	Suburban	35	1426	0.66	6.52	882.53
	Urban	0	36	0.11	2.78	2329.85

percentage growth in land-use development type in the urban classification, the Mount Baker proximal zone has its greatest percentage growth (2160 %) in the suburban classification. These unique Mount Baker proximal area results are largely due to the forecast suburban and exurban sprawl that many surrounding cities such as Bellingham, Mount Vernon, Sedro-Woolley, and Everett are expected to experience throughout the twenty-first century (Fig. 3). Overall, these findings suggest that not only is residential development expanding outward from central business districts through time, it is becoming more concentrated. It is not solely the expansion of built-environment components such as HUs and infrastructure that leads to greater volcanic disaster potentiality; rather, it is the sprawling nature of built-environment growth coupled with a densification of population and HUs in developed regions.

From 1940 to 2100, all local volcano hazard zones are forecast to lose at least 25 % of their land area classified as rural (Table 7). The Glacier Peak and Mount Baker hazard zones are expected lose the highest amount (85 %) of rural land from 1940 to 2100 compared to the other zones. Moreover, the Glacier Peak local hazard analysis has the greatest growth in urban land use with an 8650 % escalation during the 160-year period. Communities such as Mount Vernon-Burlington, Sedro-Woolley, Starwood, Arlington, and Darrington are largely responsible for the predicted intensification in urban, suburban, and exurban land use within the Glacier Peak local hazard zone because of their rapid expansion from 1940 to 2100. However, portions of Sedro-Woolley and Darrington will be

Table 7 As in Table 5, except for local hazard study regions

Area	Land-use type	Count		% of total area km^2		% Change 1940–2100
		1940	2100	1940	2100	
Baker (A2)	Rural	54,134	8151	86.43	13.00	−84.94
	Exurban	7947	49,097	12.69	78.28	517.81
	Suburban	543	5163	0.87	8.23	850.83
	Urban	7	312	0.01	0.50	4357.14
Glacier Peak (B1)	Rural	52,237	7507	86.96	12.48	−85.63
	Exurban	7321	45,534	12.19	75.72	521.96
	Suburban	510	6744	0.85	11.21	1222.35
	Urban	4	350	0.01	0.58	8650.00
Rainier (B1)	Rural	44,737	20,125	86.51	38.86	−55.01
	Exurban	6041	17,932	11.68	34.62	196.84
	Suburban	910	11,809	1.76	22.80	1197.69
	Urban	28	1924	0.05	3.72	6771.43
St. Helens (A2)	Rural	27,255	20,445	96.12	72.11	−24.99
	Exurban	1025	7192	3.61	25.37	601.66
	Suburban	75	655	0.26	2.31	773.33
	Urban	0	62	0.00	0.22	6200.00
Hood (A2)	Rural	9907	5298	81.93	43.81	−46.52
	Exurban	2150	5333	17.78	44.10	148.05
	Suburban	35	1426	0.29	11.79	3974.29
	Urban	0	36	0.00	0.30	3600.00

limited in future growth because of protected environmental lands (e.g., recreational river areas) within the Glacier Peak local hazard zone.

The Mount St. Helens local hazard zone is forecast to contain the least amount of rural land loss (25 %) from 1940 to 2100, largely due to the lack of major population centers in the volcanic hazard zone. For instance, the Mount St. Helens local hazard zone contains the greatest percentage of rural land by 2100 at 72 %, so isolated communities such as Castle Rock and Lexington are forecast to be responsible for the majority of the large urban (6200 %), suburban (773 %), and exurban (602 %) growth (Table 7). Caution should be taken with the large percentage increase in urban land use given that there was no urban classified land use 1940 and, in 2100, there is only 0.62 km^2 of forecast urban land use within the Mount St. Helens local hazard zone.

Similar to the Mount St. Helens local hazard zone analysis, the local hazard zone associated with Mount Hood is projected to undergo 3600, 3975, and 148 % increases in urban, suburban, and exurban land use, respectively, while losing up to 47 % of its rural land (Table 7). A majority of this growth is attributed to the sprawling urban, suburban, and exurban areas of the eastern Portland suburbs (e.g., Gresham) as well as the Mount Hood resort towns of Brightwood and Welches (Fig. 3). While the city of Gresham signifies the more typical urban, suburban, and exurban growth explosion that has commonly occurred in major cities throughout the twentieth and early twenty-first centuries, much of the growth in Brightwood and Welches is associated with the exurban-to-suburban land-use transition. Given 93 % of the Mount Hood local hazard region is appropriated as protected land, a large majority (88 %) of the 2100 HU density within the Mount Hood hazard zone is projected to be either rural or exurban.

The Mount Rainier local hazard zone has a 55 % loss in rural land use and a 6771 % expansion in urban land use from 1940 to 2100 (Table 7). Much of the urban and suburban growth is forecast to occur in cities such as Puyallup, Sumner, and Auburn, which are located along the Seattle–Tacoma Highway 162 and 167 corridors. In 1940, these cities had a variety HU density development types; however, by 2100, they are estimated to contain a majority of urban and suburban morphologies. By 2100, 27 % of the Mount Rainier local hazard zone is forecast to be urban and suburban. The projected urban and suburban land use in this zone is at least 15 % greater than all other urban and suburban local hazard zone percentages.

Communities within Northwest USA are situated in a unique geographic landscape where future population and built-environment growth may be restricted due to political, administrative, and geophysical boundaries. Urban, suburban, and exurban sprawl associated with the Tacoma–Seattle–Everett, WA MSA is limited by the Puget Sound and protected environmental lands such as the Mount Rainier National Park and Mount Baker-Snoqualmie National Forest. Similarly, the Portland-Vancouver-Hillsboro, OR-WA MSA will have its future development restricted by the Mount Hood and Gifford Pinchot National Forests. Conversely, other US MSAs have few geophysical boundary restrictions. Population and built-environment growth in these locations has a tendency to expand outward with little resistance. For example in other parts of the USA, the Dallas-Fort Worth and Atlanta MSAs are forecast to lose up to 81 % of their rural land from 1940 to 2100 while increasing their urban land use as much as 68,395 %. For comparison, only 23 % of the Northwest regional study area is projected to be of urban, suburban, or exurban land use by 2100. Protected lands and geophysical boundaries play an important role in how future development is shaped.

Future exposure and geophysical disaster potential are also controlled and constrained by these boundaries. While future growth in MSAs such as Dallas-Fort Worth and Atlanta may be comprised of equal parts sprawl and densification, the prevalence of geophysical boundaries limiting sprawl in the Tacoma–Seattle–Everett and Portland-Vancouver-Hillsboro MSAs leads to a greater emphasis on the densification constituent of the "expanding bull's eye effect" (Ashley et al. 2014). Although communities in the Northwest USA may not experience the same amount of sprawl compared to MSAs located in the eastern two-thirds of the USA, disaster potential remains enhanced due to the increased density of "targets"—i.e., humans and their possessions in harm's way.

5 Discussion and conclusion

This study examined volcanic hazard exposure change for the US Pacific Northwest by quantifying the interrelation of escalating populations and associated housing development with volcanic hazards. Population and HU growth is not evenly distributed across geographic space and has a tendency to cluster in locations, leading to urban and suburban development. For instance, we demonstrate that urban and suburban MSAs such as Seattle–Tacoma and Portland-Vancouver are much more physically vulnerable to volcanic hazards due to their amplifying built-environment exposure and relatively high volcanic hazard risk. Cities and suburbs have a tendency to grow radially from central business districts, so assessing the spatial character of exposure and its associated changes allows for a more comprehensive understanding of disaster potentiality. Previous research assessing changes in hazard exposure was limited due to scientific inputs, temporal constraints, coarse spatial resolution, and methodological restrictions. In order to remedy these constraints, we employed a fine-scale, spatially explicit housing density model that included projected IPCC socioeconomic storylines for a range of potential climate futures.

We specifically documented how an increasing and spreading population leads to amplifying volcano disaster potential within the Northwest USA. Using a geographic lens, we examined volcanic hazard exposure change at three different spatial scales (regional, proximal, and local hazard) and two different time periods (1940–2000 and 2000–2100). The regional, proximal, and local hazard-scale assessments illustrate, as expected, that there are simply more people and their possessions than ever before in the potential path of volcanic hazards, and this disaster potentiality is expected to amplify in the future. Through the proximal and local hazard analyses, we discovered that it is not simply the growth in population magnitude that is leading to greater volcano disaster odds, but it is also how the population and built-environment is distributed across the disaster landscape. The combination of population magnitude and its distribution within geographic space defines how principle constituents of vulnerability and risk are realized in a disaster event (Ashley et al. 2014).

As we demonstrated, the Northwest USA presents a unique geography where relatively high-density developed communities are positioned adjacent to protected lands that contain active volcanoes. These protected lands, which include national parks and wilderness areas, serve as development boundaries that suburban and exurban development can influence but not exceed (Hansen et al. 2014). In general, isolated communities within wilderness lands lead to environmental loss, fragmentation of a region's natural areas, and an enhanced vulnerability of those communities to geophysical hazards (Burby 1998; Kumpulainen 2006; Theobald et al. 2011). Neighborhoods that are positioned within a fragmented ecosystem often lack local political motivation to manage land use and properly prepare and mitigate potential disaster negative consequences (Kumpulainen 2006). The relatively small spatial extent of lesser dense, fragmented communities also leads to enhanced vulnerability given that they are likely to be destroyed if a hazard impacts the area (Kumpulainen 2006). Nevertheless, continued implementation and development of local mitigation strategies (e.g., land-use planning, public awareness programs) that take volcano hazard exposure, risk, and vulnerability into account will enable large MSA regions and small isolated communities alike to better prepare, plan, and mitigate future volcano disaster effects. Future research should also incorporate future hazard mitigation scenarios. By including mitigation and/or resilience layers to the future housing unit and population growth scenarios, the spatial patterns of the total developed footprint may dramatically change within and outside of the hazard zones.

In order to best mitigate potential volcano hazard impacts, efforts should be placed on environmentally friendly growth with local solutions to environment and economic issues. As outlined in the ICLUS SRES impact numbers, the more environmentally conscious and conservative B2 storyline often resulted in the fewest number of housing units and population impacted because of these characteristics. In general, local officials should continue focus efforts on those people living within the historical volcanic hazard zones as well as those within the volcano proximal areas (Pierce County Department of Emergency Management 2008; The Mount Hood Facilitating Committee 2013). Continual updates and revisions to volcanic hazard plans (e.g., Mount Rainier Volcano Hazard Plan, Mount Hood Coordination Plan) and associated lahar warning systems should be conducted as new suburban, and exurban communities continue to develop and densify. Accordingly, not only should the public and elected officials consider the current threats and measures of volcano disasters, but they should also understand how future population and built-environment growth could potentially affect vulnerability, risk, and exposure to volcanic hazards.

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