Ecosystem changes following the 2016 Kumamoto earthquakes in Japan: Future perspectives

Roy C. Sidle, Takashi Gomi, Munemitsu Akasaka,
Kenta Koyanagi

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Abstract Major earthquakes cause widespread environmental and socioeconomic disruptions that persist for decades. Extensive ground disturbances that occurred during the shallow-focus Kumamoto earthquakes will affect future sustainability of ecosystem services west of Aso volcano. Numbers of earthquake-initiated landslides per unit area were higher in grasslands than forests, likely owing to greater root reinforcement of trees, and mostly initiated on ridgelines and/or convex/planar hillslopes. Most landslides traveled short distances and did not initially evolve into debris flows; resultant sediments and wood accumulating in headwater channels can be mobilized into debris flows during future storms. Fissures along ridgelines may promote water ingress and induce future landslides and debris flows that affect residents downstream. Native grasses are at risk because of habitat fragmentation caused by ground disturbances, extensive damage to rural roads, and abandonment of traditional pasture management practices. Sustainable management of affected areas needs to consider future risk of cascading hazards and long-term socioeconomic impacts.

Keywords Cascading disasters · Ecosystem resetting · Landslides · Natural hazards · Semi-natural grasslands · Tipping points

INTRODUCTION

Major earthquakes often impart significant changes to landscapes due to associated uplift, subsidence, ground shaking, and large mass movements (Castilla 1988; Atwater et al. 2001; Meunier et al. 2008; Vina et al. 2011). While scholarly discourse abounds on disaster resilience (both ecological and human) (Adger 2000; Walker et al.

2004; Folke 2006; Manyena 2006; Cutter et al. 2008; Rockström et al. 2009; Gunderson 2010; Steffen et al. 2015), the concepts of disaster-related ecosystem resetting and tipping points have only recently been discussed within the contexts of ecosystem services and sustainability assessments (Sidle et al. 2013; Nel et al. 2014; Ágústsdóttir 2015). Most assessments consider ecosystems as basically static or resilient, largely due to a reluctance or inability to evaluate magnitude–frequency of various disasters along with interrelationships among major disturbances (e.g., cascading hazards) within a socioeconomic context (Sidle et al. 2013). Herein, we define sustainability as the harmonization of environmental, economic, and social opportunities for the benefit of present and future generations, while maintaining the quality of land resources.

Mass extinctions represent the most dramatic examples of ecosystem resetting (Thorne et al. 2011), but more contemporary resetting has resulted from volcanic eruptions, earthquakes, tsunamis, widespread landslides, extreme floods, and prolonged droughts. A conspicuous recent example of resetting is the 2011 Great East Japan Earthquake that triggered a series of cascading disasters, including huge tsunami, fires, landslides, debris flows, subsidence/uplift, and release of radioactive material from the tsunami damage to the Fukushima Nuclear Power Plant (Kato et al. 2012; Sidle et al. 2013). Ecosystem perturbations of a more local scale, such as flooding (Thibault and Brown 2008; Milner et al. 2013) and debris flows (Kobayashi et al. 2013), may fragment or even reset parts of the landscape, with adverse impacts on aquatic organisms and riparian communities along river networks. The 1999 Chi-Chi earthquake ($M = 7.6$) in Taiwan caused extensive surface disturbance and landslides in Choushui River catchment, but far more landslides and debris flows were triggered by subsequent heavy rainfalls during the

next two years, largely attributed to destabilizing effects of the earthquake (Lin et al. 2006a). Landslides initiated during the 1923 Kanto Earthquake in headwaters near Tokyo increased downstream sediment yields for many years (Koi et al. 2008). Volcanic activities also reset ecosystems, including widespread lava flows (Deligne et al. 2013), tephra deposits (Ágústsdóttir 2015), and lahars (Oba et al. 2004). Key to these disturbances is that intrinsic ecosystem processes or characteristics (e.g., flow paths, soil productivity, landforms, biodiversity, sediment regime) are altered for the foreseeable future.

The 2016 Kumamoto earthquakes present challenges for assessing the effects of major disturbances on long-term ecosystem services and sustainability. These challenges include the initial damages and ecosystem resetting caused by intense ground shaking, and the subsequent potential for emergence of tipping points or resetting of impacted ecosystems associated with future geomorphic, hydrological, ecological, and socioeconomic change. Ecosystem resetting in the impacted region west of Aso central cones, where the most severe shaking occurred, has strong implications for sustainable management of natural resources. Therefore, long-term ecosystem services and sustainability are very much complicated due to localized earthquake shaking, together with antecedent conditions related to local population and land use. Herein, we examine how current and future resetting, as well as the emergence of tipping points, caused by land deformation may affect various ecosystem services, including cascading or cumulative effects of the earthquake on ecosystem sustainability. These services include water resources, maintenance of traditional livelihoods, agricultural crops, tourism, and distribution and productivity of semi-natural grasslands.

ASSESSMENT FRAMEWORK

Ecosystem resetting, tipping points, and resilience

Ecosystem resetting can be described as abrupt changes to the environment that occur during episodic disasters, either triggered by natural hazards or anthropogenic stressors (e.g., toxic chemical spills, nuclear disasters) that have very long-term effects on the environment and/or ecosystem function (Sidle et al. 2013). These episodic events exceed thresholds of resilience, while resilient ecosystems tend to return to a quasi-equilibrium state following minor to moderate perturbations (Scheffer et al. 2001; Walker et al. 2004; Folke et al. 2010) (Fig. 1). The social and ecological discourse on resilience and the interactions between these two domains has implied both that societies tend to be more resilient than ecosystems (Folke 2006) and vice versa

(Adger 2000). Other learned discussions have focused on how human activities (including climate change) are pushing ecosystems beyond stable or resilient states (Rockström et al. 2009; Gunderson 2010; Steffen et al. 2015). However, there has been little focus on how episodic natural events like earthquakes, tsunamis, widespread landslides, and volcanic eruptions can move ecosystems beyond the realm of resilience (Gunderson 2010; Sidle et al. 2013; Ágústsdóttir 2015). A complicating factor is how human activities and interventions exacerbate and ameliorate, respectively, effects of certain natural hazards, particularly earth surface processes (Bergeron et al. 2006; Sidle and Ochiai 2006; Ágústsdóttir 2015; Vietz et al. 2016).

Ecosystem resetting creates social stress among the most vulnerable inhabitants, necessitating adaptations in behavior or changes in the focus of rehabilitation practices (Fang et al. 2016; Knight and Goff 2016; Lim Mangada 2016). Ecosystem resetting differs from tipping points, which emerge when chronic changes and disturbances push systems beyond their resilience thresholds to a state where it is difficult to return to their former condition (Scheffer et al. 2001; Lenton et al. 2008; Sidle et al. 2013) (Fig. 1). The concepts of ecosystem resetting, tipping points, and resilience are discussed in the context of the rural region most affected by the 2016 Kumamoto earthquakes.

Impacted study area

The primary study area is within two adjacent catchments located where the greatest ground shaking occurred during the 2016 earthquakes: Tokosegawa (6.9 km²) and Nigorigawa (6.1 km²) located west of Aso central volcanic cones within Aso Caldera (32°53′7.53″N; 131°0′23.11″E), Kumamoto Prefecture, Kyushu Island, Japan (Fig. 2). These catchments are along the edge of the Futagawa right-lateral fault, which triggered the strongest earthquake on April 16, 2016. The National Research Institute for Earth Science and Disaster Resilience estimated the maximum seismic intensity within the catchments at 6– to 6+ (Japanese scale) during the mainshock at 01:25; based on the USGS ShakeMap, estimated maximum seismic intensity on the Modified Mercalli scale ranged between VIII and IX (Fig. 2b). Elevation of the catchments ranges from 277 to 1326 m and mean hillslope gradient is 16.7°. Mean annual precipitation and temperature during the past three decades is 2832 mm and 13 °C, respectively (AMeDAS, Aso-Otohime, 8 km northeast of catchments).

Geology and soils of the study area are heavily affected by ongoing volcanic activity. Underlying geology consists of volcanic deposits (mostly tuff and basalt), with rhyolite from 2 to 5 m below the surface (Miyabuchi 2016). This area produces pure groundwater for residential and

Fig. 1 Conceptual diagram illustrating the bounds of ecosystem resilience and the difference between tipping points and ecosystem resetting when thresholds are crossed by chronic and episodic perturbations, respectively

industrial sectors (Oshima 2012), and numerous springs emerge in headwaters of the Kuma River contributing flow through Kumamoto city. Land cover in these catchments is primarily forest and grassland (Fig. 2d). Land cover in the catchments at the time of the earthquake was 54.7% Japanese cedar (*Cryptomeria japonica*) and cypress (*Chamaecyparis obtusa*) forests; 29.7% grassland, dominated by silver grass (*Miscanthus sinensis*); and 15.6% residential or cultivated land.

Land-use/cover change prior to the 2016 earthquake

Semi-natural grasslands in the Aso region have flourished for more than 11 centuries supported by regular burning, grazing, and mowing to ensure consistent growth and prevent encroachment of trees. From 1930 to 2007, grasslands decreased from 76% of the catchment area to 24%. Such drastic land cover changes are related to promotion of monoculture plantation forests together with increases in land abandonment. The conversion of grassland to forests after the 1950s was associated with post-war afforestation led by the Japanese government to satisfy growing timber demand during redevelopment. More recent land abandonment is likely attributed to aging

farmers, out-migration, afforestation, and conversion to reclaimed, intensively managed grasslands (Koyanagi et al. 2017) (Fig. 3). These ongoing losses of grassland and related ecosystem services not only decrease current population size of particular vegetation species, but also affect future population size due to time-lagged responses of species to landscape disturbances (Koyanagi et al. 2017).

Farmland abandonment may be related to severity of disaster damage. For instance, earlier reports indicate higher farmland abandonment after floods and debris flows associated with damaged land and irrigation networks south of Mount Aso (Noguchi and Nakajima 2010). Once land is unmanaged, grassland gradually converts to shrubs and immature forests (Cramer et al. 2008; Koyama et al. 2017), making conversion back to productive pastureland difficult. The relative abundance of grasslands can shift long-term legacies of interactions between vegetation and soils. Because grasslands (including endangered grass and herb species) in this area require open burning and mowing to maintain productivity (Koyama et al. 2017), high carbon stocks within soils are also maintained (Toma et al. 2010, 2013). Thus, abandonment of grasslands threatens these endangered species, even if not directly destroying them (Uematsu et al. 2010).

Fig. 2 **a** Kumamoto Prefecture on Kyushu Island, Japan highlighted; **b** area west of Aso central cones that experienced strong to violent ground shaking (Modified Mercalli scale) during the April 16, 2016 earthquake; **c** Tokosegawa–Nigorigawa catchment where landslide surveys were conducted; and **d** recent land-use and landslide locations (red circles) in Tokosegawa–Nigorigawa catchment

METHODOLOGY

We combined detailed field reconnaissance, aerial photograph analysis, and drone surveys within our study catchment, together with examining recent news and data releases and discussions with residents and professionals in the greater affected region. Landslide locations, shapes, and areas within a heavily impacted region (12.8 km²) west of the Aso central cone group were identified through stereoscopic analysis of aerial photographs (1:5800 scale) taken on April 29, 2016, 2 weeks after the main earthquake shocks. Total rainfall observed between the main shocks and the filming date was 178 mm at the nearest weather station, Otohime AMeDAS (Automated Meteorological Data Acquisition System). Scar zones of landslides were identified via stereo vision on aerial photographs and mapped in ArcGIS for Desktop (ver.10.3). Geomorphic analysis of landslides was conducted using DEM (Digital Elevation Model) data provided by Geospatial Information Authority of Japan (Digital map, 10 m grid). Slope gradient of landslides is defined as mean gradient of hillslopes in areas where landslides occurred, calculated by ArcGIS. We

assessed the spatial extent of landslides for different land covers across a range of slope gradient categories based on GIS analysis. Landslide numbers, mean size, mean gradient, mean altitude, density, and percent of total land area affected were assessed in forests, grasslands, and populated/cultivated areas using GIS. Spatial extent and distribution of various land covers were also assessed by GIS spatial analysis (ver. 10.3) and temporal changes dating back to 1930 were analyzed and overlain with earthquake-triggered landslide locations on land cover maps (Fig. 3).

EARTHQUAKE CHARACTERISTICS AND DAMAGES

The Kumamoto earthquakes consisted of a large (M_j 6.5) foreshock on April 14, 2016, followed 28 h later by the major (M_j 7.3) tremor. Between and just after these events, five other major shocks occurred, ranging from M_j 5.4–6.4. Because of the magnitudes and shallow focal depths of these earthquakes (about 10–12 km), intense ground shaking occurred (Fig. 2). The very high shaking intensities

Fig. 3 Distribution of semi-natural grasslands from 1930 to 2007 within the study catchment; locations of landslides triggered by the 2016 Kumamoto earthquake (red dots) are overlain on maps

during the foreshock and major tremor were the first successive disturbances of this magnitude ever recorded in Japan.

The most intense shaking occurred east of the city of Kumamoto in a rural area west of Mount Aso, an active volcano in Kyushu (Fig. 2). Two small communities were affected by the most intense shaking, Mashiki Town and Nishihara Village, with the greatest structural damage occurring during the mainshock in Mashiki, due to strong east–west seismic velocity components (Kawase et al. 2017). Even though most of the strong shaking occurred in rural areas, at least 49 people were killed, 372 seriously injured, and 1312 slightly injured during the earthquakes. Nearly 8000 homes were destroyed and more than 120 000 other homes were damaged (Asian Disaster Reduction Center 2016; Goda et al. 2016). Long-term disruptions occurred along roads and railways in the region.

Direct earthquake damages in the greater Kumamoto region are estimated at \$22–43 billion USD (Asian Disaster Reduction Center 2016; Goda et al. 2016). These estimates largely comprised damages to buildings, roads, railways, and other infrastructure. Estimated damages to forestry businesses were initially \$159 million USD. Indirect

damages, such as physical and psychological health issues of people confined to evacuation shelters, temporary closure of businesses, loss of work or educational opportunities, excessive travel times due to road and railway closures, and loss of tourism, were not systematically quantified, nor were environmental damages and related ecosystem services.

LANDSCAPE CHANGES DUE TO LANDSLIDES

Our observations confirmed the extensive ground deformation reported in the near-fault region where numerous buildings and infrastructure were damaged (Asian Disaster Reduction Center 2016; Goda et al. 2016; Sugito et al. 2016; Kawase et al. 2017). These deformations included ground surface ruptures near active faults, fissures along ridgelines and on convex hillslopes, zones of subsidence, liquefaction, and lateral spreading in wet areas. Additionally, many landslides were triggered in forest and grassland hillslopes on the west side of Aso central cones (Fig. 4a, b). Because these volcanic soils are well-drained and were relatively dry during the earthquakes, occurrence of debris

Fig. 4 Landslides located on the west side of Aso central cones that initiated during the 2016 Kumamoto earthquakes. **a** in forested areas; **b** in grasslands; **c** along inner gorges with sediment and debris accumulating in channels; **d** uplifted soil blocks along disintegrating ridgeline; **e** in grasslands; **f** along ridgelines; **g** sediment and debris accumulation in channels; **h** disrupted ridgeline; **i** blocky nature of failed volcanic soils which mobilized only a short distance (note grass mats intact); and **j** in steep grasslands

flows was limited. Instead, most landslides traveled short distances and consisted of ruptured blocks of cohesive volcanic soil reinforced by dense surficial mats of grass roots (Fig. 4i). In forests, landslides transported trees into and around headwater streams, creating complex log jams that affect aquatic habitat and sediment transport, but the initial propagation of debris flows was very limited (Fig. 4c, g). Landslides typically initiated along ridgelines or on convex/planer slopes due to amplifications of seismic waves in these areas (Fig. 4c, e, f, j). Such slope positions are different compared to locations of most rainfall-triggered landslides, which usually occur where subsurface water concentrates (Sidle and Bogaard 2016).

Landslides in grasslands occurred over a wide range of slope gradients (10–50°) and the shape of landslides was unique – most were rectangular with the downslope portion of the slide nearly as wide as upslope (Fig. 4e, j). Earthquake-initiated landslides occupied 2.2% of the entire catchment area, but more landslides per unit area occurred

in grasslands compared to forests despite the slightly steeper gradients of forested areas (Table 1). Few landslides in forests initiated on slopes < 20° and > 35°, and the highest densities of landslides occurred on slopes of 20–35° (Fig. 5). The higher density of landslides in grasslands compared to forests in terrain steeper than 30° may be attributed to the relatively shallow and weaker root strength of grasses (Marden and Rowan 1993). In higher elevation forest sites, large displaced soil blocks were also common in landslide deposits and were thrust to the surface on ridgelines during the shaking (Fig. 4d, h).

Individual landslide scars triggered during the earthquake were larger (mean landslide area: 1510 m²) than those that occurred during earlier rainfall events (200–600 m²) (Miyabuchi and Daimaru 2004). Soils in landslide deposits in grasslands were not thoroughly mixed because of the blocky nature of failed materials (Fig. 4i). In forested areas, especially near ridgelines or on convex slopes, trees were uprooted and transported downslope,

Table 1 Landslide statistics for different land cover classes within the 13 km² catchment

Land cover	Area (km ²)	% total area for various land uses	Number of slope failures	Landslide density (km ⁻²)	Mean landslide area $\pm$ SD (m ²)	% area in landslides	Mean slope gradient of landslides (°) $\pm$ SD	Mean altitude landslide initiation $\pm$ SD (m)
Forest	7.0	54.7	106	15.1	1551 $\pm$ 1708	2.3	29 $\pm$ 7	923 $\pm$ 176
Grassland	3.8	29.7	77	20.3	1524 $\pm$ 2546	3.1	28 $\pm$ 8	802 $\pm$ 162
Populated or cultivated	2.0	15.6	7	3.5	753 $\pm$ 577	0.3	15 $\pm$ 8	477 $\pm$ 45
Total	12.8	100	190	14.8	1510 $\pm$ 2017	2.2	28 $\pm$ 8	859 $\pm$ 192

Fig. 5 Percent of landslide area in various slope gradient categories within grasslands and forests

creating partial log jams (Fig. 4d, g). Damage to rural roads that access forest and grassland sites was widespread, thus impeding future management of these ecosystems. About 500 km of paved roads became inaccessible because of ground deformations, collapses, and damage to bridges in the greater Kumamoto area. In addition to major roads, many secondary agriculture and forestry access roads remain closed.

FUTURE RESETTING OF THE LANDSCAPE AND POTENTIAL IMPACTS

Because many earthquake-triggered landslides occurred along ridgelines, some sharp ridges are disappearing due to failures along both sides of slopes (Fig. 4a, d, h). Future landslides along ridgelines will likely occur at sites where large fissures (> 1–2 m deep) appeared during the earthquakes (Fig. 6). These fissures can preferentially route rain water and runoff into the soil mantle, thus augmenting pore water pressures that would trigger landslides in future storms. As these landslides occur, more ridgelines will disintegrate causing major topographic changes, possibly resetting channel networks. At finer scales, exposed

bedrock or compacted soil layers will affect infiltration patterns and localized flow pathways. Such geomorphic changes have strong implications for surface and subsurface flow that affect the amount and timing of runoff to downstream agricultural, municipal, and domestic water supplies because of alterations in water routing and residence times.

Existing and future ground and vegetation disturbances may accelerate ongoing declines of grasslands with associated socioeconomic and demographic impacts. While grasses may survive on displaced landslide blocks, the highly disrupted topography discourages future cattle grazing, promotes overland runoff, exacerbates surface erosion, and affects species composition (Fig. 4i). Earthquake disturbances also accelerate future damage and loss of productivity of affected lands by reducing road access and imposing barriers to management. The collapse of many farm buildings during the earthquake caused some cattle farmers to abandon their business, indicating feedbacks between social and ecosystem sustainability. As an example, out-migration from rural Minamiaso village, just south of our study catchments, increased nearly two-fold from 2015 to 2016 following the earthquake.

Landslides and mixing of surface and deeper soils may affect nutrient conditions and cycling (Adams and Sidle 1987; Turner et al. 2012), including carbon stocks; these may be depleted if grasslands become unmanaged. Invading successional vegetation may use more nutrients than native grasses, thus impacting productivity. Future land management in this reset ecosystem needs to be re-evaluated based on land use and disturbance legacies of specific catchments. For example, distribution of forests and stand conditions in damaged areas can be rearranged to be more resilient against landslides and debris flows, especially in and around zero-order basins (Sidle et al. 2000). Maintaining forest stand density is also important for reducing flood damages associated with log jams and transported wood. However, such rearrangement of land cover would require coordinated multidisciplinary approaches.

Changes in distribution of endangered species in grasslands (i.e., *Echinops setifer*, *Asparagus oligoclonus*,

Fig. 6 Fissures $\approx$ 1–2 m deep along ridgelines that formed during the earthquake; schematic to right illustrates how fissures can preferentially route water deep into the soil and trigger later landslides

Polemonium caeruleum subsp. *Kiushianum*, *Lychnis kiusiana* Makino) and habitat damage may result due to landslides. Because many endangered grassland species in this region, including those endemic to Aso, seem to have limited seed dispersal (Koyanagi et al. 2017), direct destruction of habitat may increase the risk of local extinction. Given this limited distribution, localized extinction may be affected by landslide disturbances as well as subsequent sediment movement and land-use changes (e.g., abandoned grasslands).

Because even small-scale topographic attributes affect groundwater recharge (Sidle et al. 2011), realignment of catchment boundaries and alteration of surface and subsurface features that influence deep infiltration (i.e., fissures) are earthquake legacies that may change groundwater conditions in the region. Preliminary reports and newspaper accounts after the earthquakes note both increases and decreases in flow volumes. In the aftermath of the earthquakes, these springs became important water resources for local evacuees because of disrupted domestic water supply lines. Therefore, understanding locations of springs within the channel network suddenly became essential for disaster prevention and relief, in addition to their more typical role in water resources management. Changes in topographic boundaries of catchments, which occur as ridgelines disappear due to progressive landslides

(Fig. 4d, h), will alter contributing catchment areas, thus affecting flood routing and magnitude.

EMERGENCE OF TIPPING POINTS

Disturbances during and after the Kumamoto earthquakes provide an opportunity for highlighting the potential emergence of tipping points associated with geomorphic response, ecological consequences, and social and economic attributes. Landslides triggered during the earthquake on moderately steep slopes in Aso caldera carved deep channels. With the numerous ash emissions from the Nakadake crater (the active crater in Aso caldera) (Miyabuchi et al. 2008), it is plausible that a series of large ash falls could deposit sufficient ash into these landslide channels making them susceptible to debris flows and lahars during future heavy rains (Fig. 7) (Miyabuchi and Daimaru 2004). A recent significant eruption on October 8, 2016 emitted and spread ash to an altitude of 11 km and over distances up to 250 km from Nakadake crater. Future debris flows or lahars would cause considerable damage to rural environments. Another very probable tipping point may result from the following sequence of events: (a) earthquake-initiated landslides store sediment in headwater channels due to limited mobility of landslides and log jams (Fig. 4c, g); (b) surface erosion transports

Fig. 7 Examples of cascading sediment disasters that could occur following the April 2016 Kumamoto earthquakes

additional sediment into channels from landslide scars; (c) new landslides occur along ridgelines, exacerbated by fissures, adding sediment to channels (Fig. 6); (d) episodic ash fall contributes sediment to channels; and (e) once channels have accumulated sufficient sediment, coupled with a large stormflow, debris flows emerge (Sidle and Ochiai 2006) (Fig. 7). This scenario represents a cascading sequence of natural events that will generate future environmental and human risks, including impacts to water quality, sediment disasters, and damage to buildings and infrastructure. Debris flows following the earthquake have already occurred in some areas, including during storms in June 2016. Tipping points will be difficult to predict unless the interacting processes are recognized.

Ground disturbances in grasslands may contribute to ecological and socioeconomic tipping points. Given the widespread infrastructure damages throughout the region, lightly used rural roads will not be repaired soon and, in some cases, jurisdiction of the responsible caretaker of roads is unclear. While overall agriculture land abandonment (including grasslands) has occurred from the 1960s

up until near the time of the earthquake (Fig. 3), the recent combination of restricted access, damage to farm buildings, landslides in pastures, and aging land stewards will increase unmanaged grasslands. Because grasslands require regular maintenance for burning in early spring and subsequent harvesting, unmanaged conditions for more than one year caused by landslide blockage of roads and fissure development on hillslopes will affect grasslands. Furthermore, increasing out-migration from local villages underscores the earthquake impacts on traditional management. These changes affect rural community structure and demographics, as well as the ecology and long-term productivity of lands.

ROADMAP FOR ASSESSING FUTURE ECOSYSTEM CHANGES, SERVICES, AND SUSTAINABILITY

Cumulative effects of both natural and anthropogenic disturbances at various spatial scales can induce ecosystem

consequences that persist with time, cover wide areas, and may exceed additive impacts of individual effects (Sidle and Hornbeck 1991; Bergeron et al. 2006; Lin et al. 2006b; Buma et al. 2014). To predict realistic ecosystem recovery in a severely disturbed environment like Kumamoto, it is necessary to evaluate the long-term potential for cascading hazards. Here we examine how both the environmental and socioeconomic changes related to the Kumamoto

earthquakes may manifest over the period from earthquake onset to more than a century later (Fig. 8). Initial ground disturbances and structural damages occurred during intense seismic activity, but longer-term effects manifest over different temporal scales. Most of the enhanced geomorphic processes (landslides, surface erosion, channel infilling) are expected to persist for a decade, while hydrological changes may lag and follow geomorphic

Fig. 8 Trajectories of some of the likely environmental and associated socioeconomic changes following the Kumamoto earthquakes

perturbations. Grassland productivity will initially decline and then gradually recover, but species composition could change indefinitely if traditional grazing is not maintained. Downstream sediment hazards will increase for several years to a decade or more, then decline as stored sediment in channels is flushed out or if check dams are constructed. These trends will also affect water quality due to readily transportable sediment stored in both ephemeral and perennial channels (Fig. 8).

A useful spatial perspective for assessing recovery in such disturbed environments is at the larger catchment scale. Major natural hazards often affect wide areas when disasters first strike. Hence, later impacts or cascading disasters are often related to the connectivity of the affected areas to the surroundings. In this context, channel networks (or distribution of disturbed sub-catchments) are important landscape ‘connecting’ structures (Sidle et al. 2017b). For the impacted Kumamoto region, not only is the initial sediment production by landslides important, but also how such unstable sediment remains in channels and what conditions (e.g., topography, sediment accumulations, log jams) retain or facilitate the later chronic or episodic release of this sediment.

Utilizing innovative planning practices will be necessary to cope with current and future environmental changes set in motion by the Kumamoto earthquakes. Areas directly affected by episodic and chronic sediment released from headwaters and surrounding areas may benefit from applications of green infrastructure. Green open spaces and off-channel sediment basins that promote sediment deposition and allow channel shifting with increased sediment loads may be more effective than constructing expensive sediment check dams and may contribute to ecosystem services like water purification and wildlife habitat (Liao 2014). Streams affected by altered hydrologic regimes will also benefit from vegetated riparian corridors that allow for channel adjustment as opposed to channelized structures (Vietz et al. 2016). Residential and business development near floodplains of affected channel networks should be carefully assessed related to future flood and sediment hazards (Sidle et al. 2017a).

Green infrastructure can be readily applied in rural areas, sites where Japan has typically used check dams and channel structures to control downstream sediment pulses. Such practices could include rearranging land uses/land cover to help restore natural hydrogeomorphic processes and maintaining forested riparian buffers that provide depositional environments for exported sediment during high flows and trap sediment behind wood in channels. Furthermore, because monoculture Japanese cedar and cypress plantations are being less utilized as timber resources (Sidle et al. 2007), overstocked stands with high volumes of timber may exacerbate sediment disasters when

woody debris and sediment are mobilized together. Thus, ongoing sustainable forest management is essential to reduce wood-related disasters (i.e., failures of log jams) and conserve the water maintenance function of forests. To achieve this, detailed monitoring at various scales needs to focus on how disturbances alter hydrologic and geomorphic processes (Sidle et al. 2017b). Recent regional climate change patterns, including increases in annual rainfall, intensity, and the number of days with total rainfall > 50 mm (Japan Meteorological Agency 2016), will also influence how land management strategies and disaster prevention practices develop and are applied in unstable hillslopes affected by the earthquake (Sidle et al. 2017a).

CONCLUSION

Recent complex disasters such as the 2011 Great East Japan Earthquake and the 2016 Kumamoto earthquakes have reinforced the need to reassess long-term sustainability of ecosystems, societies, and their traditional economies within the context of drastically altered environments. Our investigations in the aftermath of the Kumamoto earthquakes show that in addition to the immediate infrastructure and building damages, loss of life, and extensive ecosystem disturbances, many lingering or cascading impacts on society and ecosystems will continue to affect the region for the remainder of this century. While landslides were widespread during the earthquake, extensive damaging debris flows have not yet developed, possibly due to mitigation efforts within the channels. However, when we observe hillslope conditions, it is apparent that new landslides that will occur due to fissures and ground disturbances created by the earthquake. Such failures, together with sediments stored in steep channels that did not mobilize long distances following the earthquake, will greatly increase the probability of long runout debris flows during future storms. Elevated suspended and bedload sediment yields may continue for long periods. Long-term changes in both surface and ground water routing may occur due to disintegration of ridgelines and preferential flow in earthquake fissures, respectively. Various geomorphic, ecological, and socioeconomic tipping points are likely to emerge, including interactions of these processes and stressors.

Because of impending cumulative effects and uncertainties, long-term monitoring that combines hydrologic, geomorphic, and ecological processes, focusing on hillslope-channel linkages, is needed to support future management decisions (Sidle et al. 2017b). We present a roadmap to understand these long-term cumulative effects that can be applied in other areas subject to episodic

resetting. These considerations need to be incorporated into both rural and community plans for areas at risk to insure sustainable outcomes for society and the environment.

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AUTHOR BIOGRAPHIES

Roy C. Sidle (✉) is a Professor of Geography and the Director of the Sustainability Research Centre at University of the Sunshine Coast and holds a Distinguished Professorship in the Institute of Global Innovation Research, Tokyo University of Agriculture and Technology. He is a hydrogeomorphologist with research interests in natural hazards, catchment processes, and environmental sciences with an emphasis on effects of management practices, and currently has active research programs in Australia, Japan, Colombia, and Central Asia. Address: Sustainability Research Centre, University of the Sunshine Coast, 90 Sippy Downs Dr., Sippy Downs, QLD 4556, Australia. Address: Institute of Global Innovation Research, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-5809, Japan. e-mail: rsidle@usc.edu.au

Takashi Gomi is a Professor in the Department of International Environmental and Agriculture Science at Tokyo University of Agriculture and Technology. His research focuses on catchment processes, forest hydrology, and environmental impacts of both natural and human-induced hazards.

Address: Department of International Environmental and Agricultural Science, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-5809, Japan.

Address: Institute of Global Innovation Research, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-5809, Japan.
e-mail: gomit@cc.tuat.ac.jp

Munemitsu Akasaka is an Associate Professor in the Institute of Agriculture at Tokyo University of Agriculture and Technology. He is a conservation biologist with interests in mechanisms and processes that contribute to biodiversity conservation.

Address: Institute of Agriculture, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-5809, Japan.
e-mail: muuak@cc.tuat.ac.jp

Kenta Koyanagi recently completed his undergraduate degree in environmental science at Tokyo University of Agriculture and Technology under the direction of Prof. Gomi. He is currently a Master's student in forest management at University of Eastern Finland.

Address: Faculty of Science and Forestry, University of Eastern Finland, Yliopistokatu 2, 80100 Joensuu, Finland.

Address: Tokyo University of Agriculture and Technology, Fuchu, Tokyo, Japan.

e-mail: koyanagikenta@gmail.com