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SPECIAL FEATURE: HIGH-ENERGY STORMS

Resistance and resilience of social–ecological systems to recurrent typhoon disturbance on a subtropical island: Taiwan

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Abstract. Tropical cyclones (TCs) have major effects on ecological and social systems. However, studies integrating the effects of TCs on both social and ecological systems are rare, especially in the northwest Pacific, where the frequency of TCs (locally named typhoons) is the highest in the world. We synthesized studies of effects of recurrent typhoons on social and ecological systems in Taiwan over the last several decades. Many responses to TCs are comparable between social and ecological systems. High forest ecosystem resistance, evident from tree mortality below 2% even following multiple strong typhoons, is comparable with resistance of social systems, including the only 4% destruction of river embankments following a typhoon that brought nearly 3000 mm rainfall in three days. High resilience as reflected by quick returns of leaf area index, mostly in one year, and streamwater chemistry, one to several weeks to pre-typhoon levels of ecosystems, are comparable to quick repair of the power grid within one to several days and returns of vegetable price within several weeks to pre-typhoon levels of the social systems. Landslides associated with intense typhoons have buried mountain villages and transported large quantities of woody debris to the coast, affecting the coastal plains and reefs, illustrating a ridge-to-reef link between ecological and societal systems. Metrics of both social and ecological function showed large fluctuations in response to typhoons but quickly returned to pre-disturbance levels, except when multiple intense typhoons occurred within a single season. Our synthesis illustrates that the social–ecological systems in Taiwan are highly dynamic and responsive to frequent typhoon disturbance, with extraordinarily high resistance and resilience. For ecosystems, the efficient responsiveness results from the selective force of TCs on ecosystem structure and processes. For social systems, it is the result of the effects of TCs on planning and decision making by individuals (e.g., farmers), management sectors, and ultimately the government. In regions with frequent TCs, the social–ecological systems are inevitably highly dynamic and rapid responses are fundamental to system resistance and resilience which in turn is key to maintaining structure and function of the social–ecological systems.

Key words: high-energy storms; resilience; resistance; social–ecological systems; Special Feature: High-Energy Storms; subtropical mountainous island; Taiwan; tropical cyclones.

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Introduction

Natural disturbances are a key factor influencing ecosystem development and composition in many parts of the world (Sousa 1984, Esser et al. 2001, Romme et al. 2011). Over the last several decades, discussions on disturbance and system dynamics have extended to include both social and biophysical systems, and the interactions between them, especially in the face of extreme events (Holling 1986, Adger et al. 2005). High-energy storms (HES) such as tropical cyclones are among the most widely studied natural disturbances (Nowacki and Kramer 1998, Laurance and Curran 2008). The effects of HES on social and ecological systems are intertwined, so a comprehensive understanding of the vulnerability or response of each system requires study of the other. For example, in Taiwan, a global hotspot of cyclone disturbance (Sampe and Xie 2007, Lin et al. 2011), the tragedy of buried villages caused by typhoon-induced debris flows led to the enforcement of regulations that restrict development and protect forests on steep mountain slopes. The catastrophic effects of cyclonic storms, such as Hurricane Katrina (2005) in the southeastern USA (Ashley and Ashley 2008, Shiller et al. 2012), Hurricane Hugo (1989) in the Caribbean (Walker et al. 1991, 1996, Heartsill-Scalley et al. 2007) and Hurricane Georges (1998) in Central America (Sattler et al. 2002, Van Bloem et al. 2005), Cyclone Larry (2006) in northwest Australia (Wallace et al. 2009, Hancock and Evans 2010), and Typhoon Morakot (2009) in Taiwan (Tsou et al. 2011, West et al. 2011), on social and ecological systems highlight the critical need for an integrated assessment of the resistance and resilience of social–ecological systems to cyclones.

Although many different concepts and terms have been used to describe the immediate effects of disturbances on ecological systems (e.g., Peterson and Stevenson 1992, Lavorel 1999, Orwin and Wardle 2004) or the longer-term responses of abiotic and biotic components of ecological systems to disturbance (Berumen and Pratchett 2006, Lugo 2008), we follow Waide and Willig (2012), who provide concise definitions of "resistance" and "resilience" that have been used to describe responses of a diversity of ecosystems to HES as well as other disturbances (see Walker 1991 and constituent chapters). Based on Waide and Willig (2012), "The degree to which ecosystem characteristics remain unaffected by disturbance is referred to as resistance." and "The time required for an ecosystem to return to conditions that are indistinguishable from those prior to a disturbance represents the system's resilience."

Located in the northwest Pacific, Taiwan is affected by 3–6 landfall typhoons per year (Fig. 1a), with more than a third reaching category three or greater intensity (Saffir-Simpson scale). A number of typhoons have taken heavy tolls on social–ecological systems. For example, Typhoon Soudelor (2015), which set a new record high wind speed in northern Taiwan (237 km/h), caused serious deterioration in household water quality in Taipei (Taiwan's largest city), among other effects (Fakour et al. 2016). This became a major social–political issue with fierce and unsettled debates over the role of management of upstream watersheds on deterioration of water quality (Fakour et al. 2016). While the effects of typhoons on social or natural systems have been studied separately in Taiwan for decades, only recently have integrated social–ecological assessments been attempted to evaluate the resistance and resilience of these coupled systems to typhoon disturbance (Tang and Tang 2010, Wang et al. 2012).

Typhoons have affected Taiwan, and the development of its landscape and ecosystems, for hundreds of thousands of years (Lin et al. 2006*b*, Chiang et al. 2014). Therefore, it is not surprising that ecosystems have high resistance and resilience to HES because ecosystems that lack of high resistance or resilience would not persist through the annual typhoon disturbance. Similarly, through annual experiences with such events, social systems ranging from individual households, to government agencies, to the society as a whole, have learned and adapted to frequent HES.

Some studies have examined responses of social–ecological systems to rare catastrophic HES in other cyclone-prone tropical regions (e.g., Das and Vincent 2009, Marshall et al. 2013). However, the cost–benefit ratio of mitigation is expected to be different in Taiwan compared to places where severe storms occur once a decade or less. A thorough synthesis of local studies is necessary to provide a comprehensive view of interactions within a social–ecological system dominated by frequent HES, and from that to

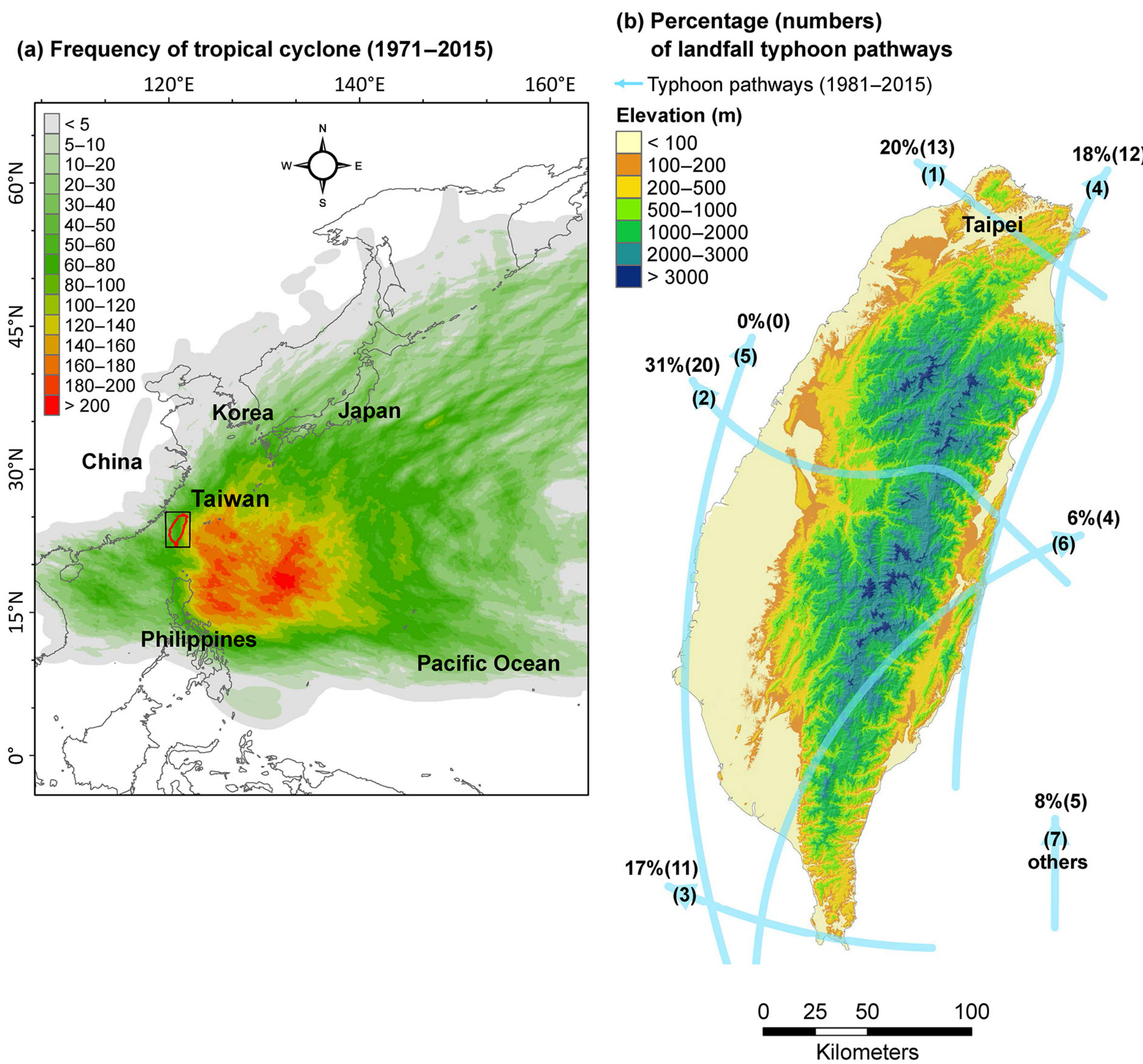
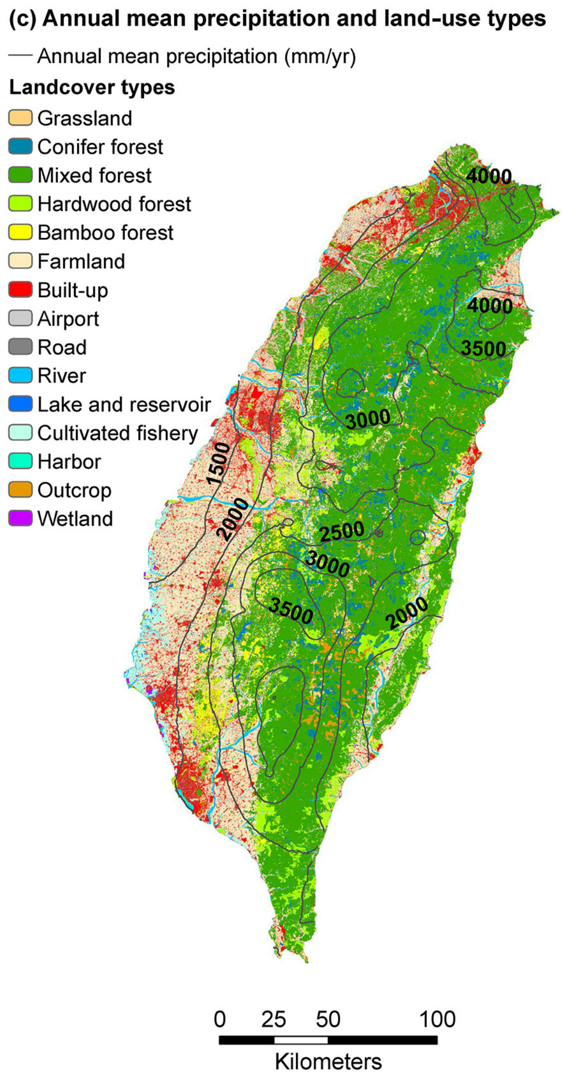


Fig. 1. (a) Frequency of typhoons in the northwest Pacific during 1971–2015 and (b) percentage and number of landfall typhoons of various paths during 1981–2015 (data from Typhoon DataBase of Central Weather Bureau of Taiwan; http://rdc28.cwb.gov.tw/).

propose adaptation or mitigation strategies that would enhance resistance and resilience.

Herein, we synthesize the current understanding of the effects of typhoons on social and ecological systems in Taiwan, and integrate knowledge to provide useful insights for enhancing social and ecological resistance and resilience to HES. More importantly, frequency, intensity, and the distribution of tropical cyclones may change with changes in global climate so that regions which currently have less frequent cyclones may experience more frequent or more intense cyclones in the future (Holland and Bruyère 2014, Kossin et al. 2016, Mei and Xie 2016). The effects of more frequent intense cyclones on social–ecological systems cannot be extrapolated from past studies based on less frequent cyclones in these regions. Because Taiwan is on the extreme end of the frequency spectrum of tropical cyclone disturbance, our synthesis opens a window to look into the potential effects of increasing cyclones on social–ecological systems for regions expected to have more frequent cyclone disturbance. The processes and management practices that contributed to the high



(Fig. 1. *Continued*)

(c) Land-use distribution in Taiwan between 2006 and 2008 (data from National Land Surveying and Mapping Centre in Taiwan; http://lui.nlsc.gov.tw/LUWeb/).

resistance and resilience of the social–ecological systems to typhoon disturbance in Taiwan could be critical checking points for predicting the effects of HES on social ecosystems but also for developing mitigating measures for regions expected to have more frequent tropical cyclones.

Geography of Taiwan

Taiwan is a 36,000-km^2 island located near the largest continent (Eurasia) and the largest ocean (Pacific), with elevations rising from sea level to nearly 4000 m within a horizontal distance of only 40 km (Fig. 1b). The current geomorphology of Taiwan was formed within the Quaternary Period (i.e., 1.8–2.59 million years ago) and so was the overall distribution of vegetation of Taiwan (Sheng 1996, 1997). Five mountain ranges bisect the island from north to south, with more than 200 peaks above 3000 m. Taiwan was formed by the active collision of the Philippine Sea Plate and the Eurasian Continental Plate, with the Philippine Sea Plate moving northwestward at a rate of approximate 7–8 cm/yr (Seno et al. 1993). Thus, Taiwan has an extremely high rate of geological uplift (5–7 mm/yr) and erosion (3.9 mm/yr) from a global perspective (Dadson et al. 2003), leading to a high rate of erosion.

The Tropic of Cancer runs through south-central Taiwan. The tropical to subtropical location and steep elevational gradient lead to diverse climate zones ranging from a tropical monsoon climate in southern lowlands to an alpine tundra climate above 3500 m. Annual mean temperature is 21.0°C with the coldest month (January) averaging 15.1°C and the warmest month (July) averaging 26.4°C. The mean annual precipitation is 2600 mm, but ranges from >4500 mm in northeastern mountains to <1500 mm at west-central coast (Fig. 1c). More than 70% of precipitation occurs in the summer growing season (May–October). Winter and spring are relatively dry in the south and west (i.e., leeward to the winter northeast monsoon), whereas the north and northeast are wet year-round (Chang et al. 2014). Precipitation associated with typhoons (July–October) accounts for ~30–50% of annual precipitation (Chang et al. 2013*a*, Lee et al. 2013).

Approximately 21 million people inhabit the island, with a large majority (>90%) in the coastal plains. Although human population density is high, 58% of the island is forested, of which 73% is naturally regenerated forests with little direct human modification over the past several decades. The remainder of the forested areas are plantations. As a result of spatial variability in climate, the vegetation of Taiwan is diverse, including evergreen broadleaf forests at low elevations, mixed forests at mid-elevations, evergreen conifer forests at high elevations, and tundra-like communities on the high peaks (Fig. 1c). Agricultural lands are concentrated in the coastal plains, with rice being the most important crop. Slightly higher elevations support unirrigated row crops.

Some agricultural lands are located in mountains, mostly in small plots producing high-value vegetables, fruits, or tea.

Typhoon Disturbance Regime

Between 1981 and 2015, 65 typhoons made landfall in Taiwan (Table 1). This number understates their effect, because Taiwan is small (<170 × 350 km) and many typhoons have large radii (>100 km). Thus, we defined typhoons that affected Taiwan as those that were <100 km from the island at their closest (Tu et al. 2009). Based on this criterion, the number of typhoons affecting Taiwan between 1981 and 2015 was 129 (i.e., 3.7 per year). Between 1970 and 2007, the northwest Pacific had the highest frequency of tropical cyclones in the world (Lin et al. 2011) making Taiwan the hottest of hotspots.

Of the 65 landing typhoons, 24 were category one, 17 were category two, and 24 were category three or higher (Table 1). Most of the landfall typhoons occurred in July and August (31% each) or September (20%), but they may occur as early as May or as late as December (Table 1). Although typhoons generally come from the southeast, they can follow very different paths across the island. Consequently, no area in Taiwan is free from typhoon disturbance (Figs. 1b, 2). Although no significant trend characterized the speed of maximum sustained wind of landfall typhoons over the last 35 yr, the speed of gust wind, total precipitation, and maximum 24-h precipitation increased significantly over the same time period (Fig. 3).

Although Taiwan is small, there is considerable variation in the frequency and severity of typhoon disturbance. For example, because most typhoons approach Taiwan from the east, western Taiwan, particularly west-central Taiwan is much less affected by typhoons due to the barrier effect of the high mountain ranges extending from the north to the south. In addition, the large elevational gradient leads to a large variation in typhoon intensities (and severity of typhoon effects), decreasing from low to high elevations (Chi et al. 2015). This occurs because large elevational gradient of typhoon intensities opens up avenues for pairing typhoon strength with system structure and functioning.

A Ridge-to-Reef Perspective

The large elevational range (0–4000 m) within a small geographic area (36,000 km^2) makes Taiwan an ideal place to illustrate the ridge-to-reef or reef-to-ridge effects of and responses to HES. This perspective also includes gradients in social and ecological systems from the mountains and the coast.

Table 1. Monthly distribution of the number of intense typhoons between 1981 and 2015 (a) within a short distance of Taiwan (<100 km) and (b) including only storms that made landfall on Taiwan between 1981 and 2015.

SS Scale	May	June	July	August	September	October	November	December	Sum
(a) <100 km from Taiwan									
1	3	10	15	17	13	1	3		62
2	1	5	6	5	4	5			26
3		2	2	8	9	4		1	26
4			4	6	1				11
5			2	1	1				4
Sum	4	17	29	37	28	10	3	1	129
(b) Landfall									
1		2	9	9	4				24
2	2	3	4	3	3	2			17
3		1	1	4	6	1		1	14
4			4	4					8
5			2						2
Sum	2	6	20	20	13	3	0	1	65

Notes: Data from Typhoon DataBase of Central Weather Bureau of Taiwan (http://rdc28.cwb.gov.tw/). Intensity classification based on the Saffir-Simpson (SS) scale. Empty cells denote zero (no record).

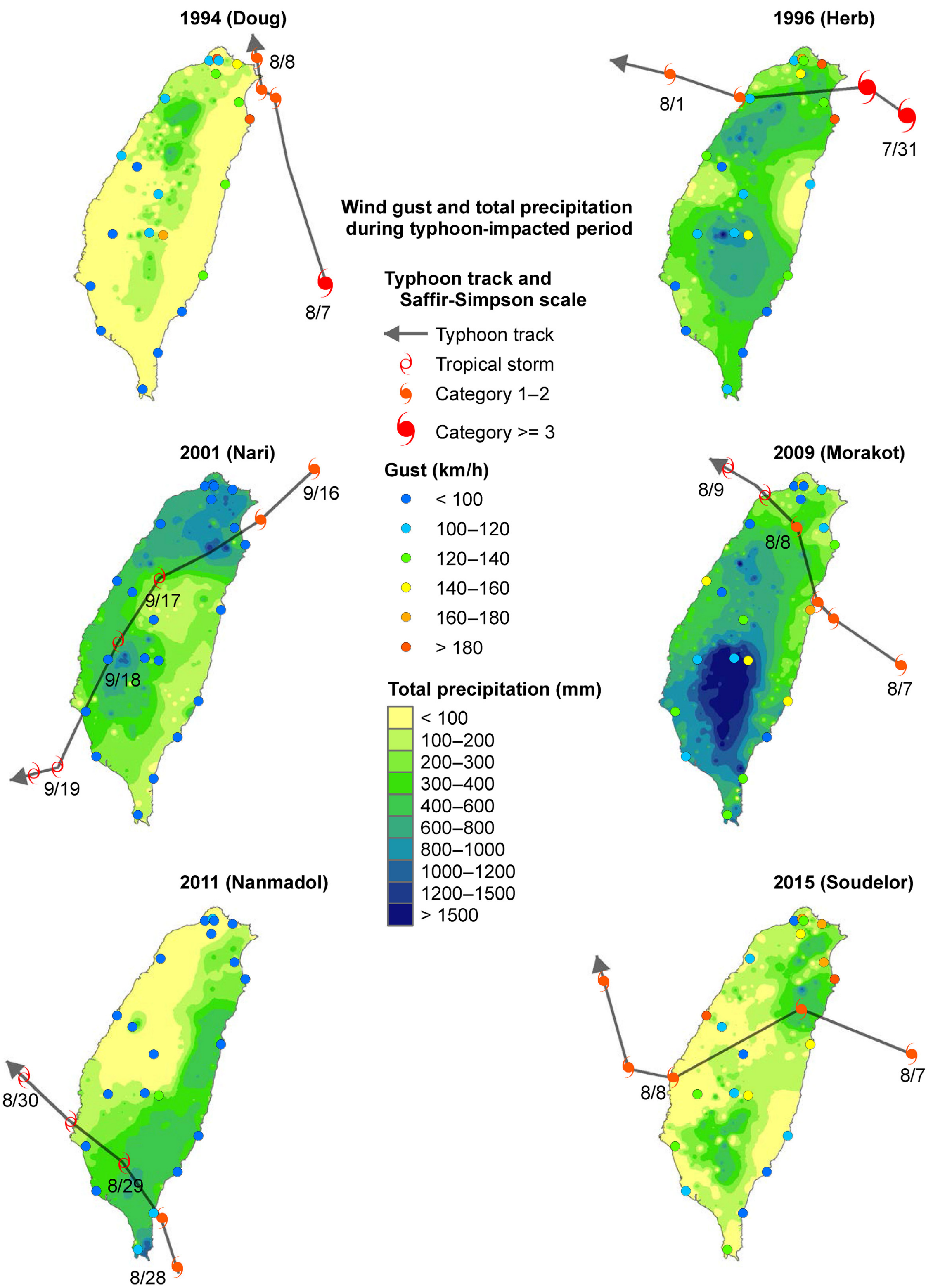


Fig. 2. Tracks and spatial patterns of gust winds and total precipitation during typhoon period for several

(Fig. 2. *Continued*)
landfall typhoons that caused severe damages to social–ecological systems in Taiwan. One typhoon was chosen to represent each of the six general storm routes (see Fig. 1b). Data from Typhoon DataBase of Central Weather Bureau of Taiwan (http://rdc28.cwb.gov.tw/).

Ecosystems

An obvious ridge-to-reef link relates to the transformation of soil and living biomass in the mountains into sediment and woody debris, respectively, which are deposited in coastal floodplains and washed offshore into reef ecosystems. Typhoon Morakot (2009) transported 3.8–8.4 Tg coarse woody debris to the oceans, representing a highly concentrated flux of carbon (1.8–4.0 Tg) and nutrients (West et al. 2011), covering 83% of Taiwan's coastline with driftwood (Chuang and Doong 2011). Particulate organic carbon (POC) fluxes and dissolved Si concentrations delivered to the ocean during typhoon Mindule (2004) were appreciable: POC flux of 5×10^5 t associated with a sediment flux of 61 Mt during a 96-h period (Goldsmith et al. 2008). The transport of POC (including coarse woody debris) during typhoons represents a loss of carbon and nutrients from terrestrial ecosystems. The periodic loss of such large quantities of carbon and nutrients may account for apparent contradictions between low biomass at many low-elevation natural forests in Taiwan that are characterized by high inorganic nitrogen input (22 $kg \cdot ha^{-1} \cdot yr^{-1}$) and retention (80%), high plant nitrogen uptake, and high net primary productivity (NPP; Huang et al. 2016). Human activities also play an important role in predisposing parts of the landscape to catastrophic erosion during typhoons. Areas with recent land-use change had proportionally more landslides than did non-changed areas during typhoon Morakot (Chen and Huang 2013). In other words, reciprocal feedbacks exist between the social and biophysical systems in the ridge-to-reef link of translocation of soil and elements.

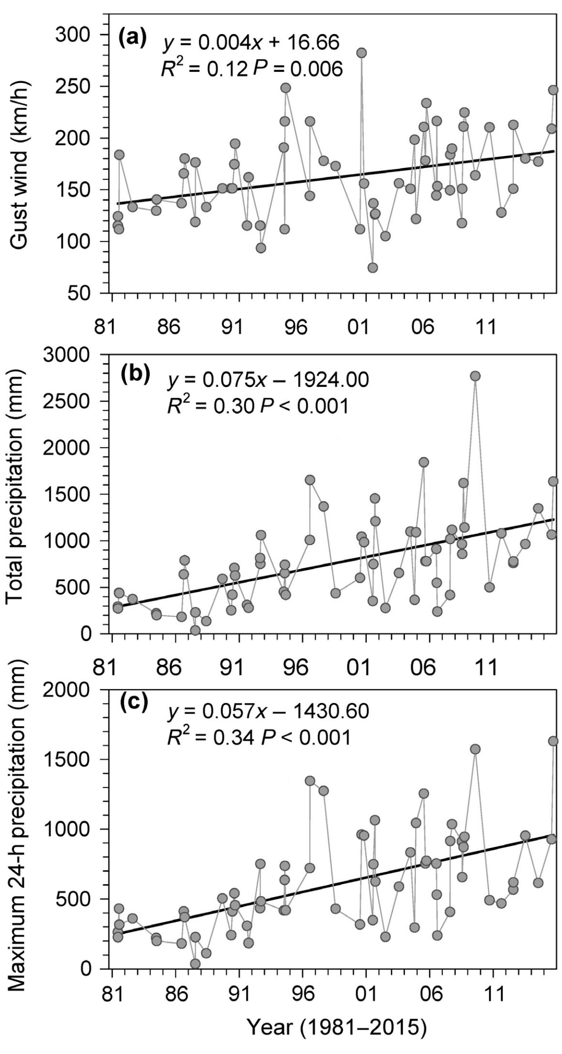


Fig. 3. Temporal trends (linear regression fit by least square analyses) of (a) gust wind (km/h), (b) total precipitation (mm), and (c) maximum 24-h precipitation (mm) of typhoons making landfall to Taiwan between 1981 and 2015. Data from Typhoon DataBase of Central Weather Bureau of Taiwan (http://rdc28.cwb.gov.tw/).

The ridge-to-reef or reef-to-ridge response to typhoon disturbance is also evident in forest structure. Taiwan is characterized by an unusual pattern of increasing forest stature and aboveground biomass from low (770 m) to high elevations (3000 m), which has been attributed to greater typhoon wind effects (dwarfing) at low rather than high elevations (Chi et al. 2015). These effects arise because as a typhoon moves upslope, the rough topography and cooler temperature weaken it (Chi et al. 2015). Decreases in forest stature and aboveground biomass from low to high elevations are widely seen around the globe and can be attributed to the harsher growth conditions at high elevations (e.g., low temperature, low soil stability, poor soil aeration, and high winds). However, high winds from typhoons remove taller trees, limiting the vertical development of forests in Taiwan (Chi et al. 2015). Also, frequent disruptions (defoliation, removal of taller trees) by typhoons interrupt the accumulation of biomass, resulting in short stature and low biomass forests at more severely affected low elevations. This process also results in the lower heterogeneity of canopy tree height at low elevation than at high elevations (Chi et al. 2015). Thus, the reef-to-ridge response of forest structure and aboveground biomass to typhoon disturbance in Taiwan illustrates that like prevailing climate, HES have the potential to affect broad-scale ecosystem structure (e.g., forest stature) and function (e.g., carbon accumulation).

The ridge-to-reef transport of large quantities of water, sediment, and driftwood also harms reef systems. Typhoon Morakot substantially decreased the coverage of the dominant coral species, *Montipora aequituberculata*, from 33% to 5% in Siangjiao Bay in southern Taiwan, with most areas transformed into bare rocks covered by turf algae (Kuo et al. 2011). Freshwater runoff associated with Typhoon Morakot strongly influenced copepod species composition in the estuary of northern Taiwan, with the dominant species changing from *Pseudodiaptomus annandalei* before the typhoon to *Acartia spinicauda* during post-typhoon period (Beyrend-Dur et al. 2013). The reef system in southern Taiwan has experienced six typhoons and two coral-bleaching events between 1985 and 2010 (Kuo et al. 2012). These disturbances have resulted in the decline of all hard coral species (a reduction in hard coral cover from 47.5% in 1985 to 17.7% in 2010) and an increase in macro-algal cover (11.3% in 2003 to 28.5% in 2010, Kuo et al. 2012). Typhoons are not new to the coral system in southern Taiwan. Consequently, it is not clear what role recent major typhoons have had in the observed coral community change. Currently little is known about the resistance or resilience of coral communities to HES.

Social systems

Although forest dwarfing is a good example of the effects of or adaptation to frequent typhoon disturbance at low elevations, the unique location of Lanyu, a coral island southeast of Taiwan, provides an excellent example of social adaptation to HES. In Lanyu, traditional houses of the aboriginal Tao tribe are built partially belowground, and each has a drainage system (Fig. 4) to minimize damage from both wind and flooding, in addition to mitigating high temperatures. The Tao people is the only oceanic aboriginal tribe in Taiwan, though their origin is under debate. One hypothesis is that they are from the tropical Bataan Islands of the Philippines. The exact time of their arrival to Lanyu is unknown, but it is generally agreed that they have been

Fig. 4. Traditional houses (those with black roofs) at Lanyu (a small island off the east coast of Taiwan), constructed mostly below ground with a drainage system to resist typhoon effects as well as mitigate summer heat.

living on the island for several thousand years and have centuries of experiences involving typhoon disturbance (Digital Museum of Taiwan Indigenous Peoples 2017). Their traditional houses are being replaced by modern concrete buildings, which can sustain even the most intense winds associated with typhoons, but are not free from the threat of flooding associated with heavy precipitation.

During most typhoons, the greatest precipitation occurs in the mountains (Fig. 2), such that the risk of debris flows is high. Debris flows harm the coastal tourism and fishing industries, and endanger navigation and maritime activities (Chuang and Doong 2011). The social effects of debris flows are highest in low-elevation mountain areas where the inhabitants are mostly aboriginal peoples who were forced to move to the mountains when the Han people migrated from southeastern China to Taiwan, approximately 400 yr ago. An island-wide monitoring system for debris flows was established in 2001 to provide real-time warnings to enable timely evacuation when the risk exceeds a critical threshold (SWCB CA 2011). The establishment of the monitoring system was the result of several tragedies in which mountain villages were buried by typhoon-induced debris flows. For example, a debris flow during Typhoon Herb (1996) buried a village in central Taiwan, causing 51 casualties (Yu et al. 2006). Similarly, debris flow during Typhoon Morakot buried the Shaolin village with a death toll of approximately 500 (Tsou et al. 2011). Although debris flows and flooding in the mountains are caused by high precipitation, flooding in low-lying cities is often associated with both heavy rainfall and storm surge. For example, Typhoon Nari (2001) brought approximately 1000 mm rainfall to northern Taiwan (Fig. 2). The most severe flooding during Typhoon Nari was not on the coast. Rather, it was approximately 30-km inland from the estuary of the Danshui River, at Shitsu (which means "where the tide stops"), where flooding was as high as 9 m. The serious flooding associated with Typhoon Nari in Shitsu damaged the power system, which is primarily located in basements of buildings. To avoid this in the future, power systems are being moved to higher floors. In a way, the legacy of typhoon damage changed the design of modern buildings as an adaptation or response to improve the resistance of the social system. A similar scenario occurred in New York City following Hurricane Sandy (2012) in which power infrastructure in basements was heavily affected, followed by a major effort to move electrical and other utility components to aboveground levels (Force 2013).

Typhoon Disturbance in Relation to Coupled Social–Ecological Systems

In regions where tropical cyclones occur once every decade or less, extreme events such as Hurricane Hugo or Hurricane Georges in the Caribbean Basin, Hurricane Katrina in the southeastern USA, or Cyclones Larry and Monica in Australia often attract a large number of scientists to study the characteristics and effects of infrequent events. Collective efforts to study a particular storm provide a comprehensive understanding of social–ecological effects of such extreme events in these regions. In contrast, in places such as Taiwan, where typhoons occur on an annual basis, study effort is distributed among various typhoons (with somewhat more attention given to the strongest storms). Because every typhoon is unique, knowledge gained from any particular typhoon cannot represent all typhoon-related disturbance effects. Instead, the cumulative efforts that span a number of typhoons and several decades provide the most comprehensive understanding of short-term and long-term effects on social–ecological systems. Moreover, understanding based on a large number of cyclonic storms that encompass a wide range of wind velocities, rainfall quantities, storm surges, durations, and timings is particularly valuable for the development of adaptation strategies and management practices for enhancing the resistance and resilience of social–ecological systems.

Resistance and Resilience

Ecosystems

High resistance of community structure is key to the high functional resilience (e.g., quick return of nutrient cycling or vegetable market to predisturbance levels) of ecosystems in Taiwan. For example, tree mortality (measured as the proportion of trees uprooted or bole-snapped) at the Fushan Experimental Forest (FEF), a low-elevation

(670–1100 m) forest in northeastern Taiwan, was only 1.4% following four typhoons (3 category three and 1 category one) in 1994 and <1% following category-three Typhoon Herb in 1996 (Lin et al. 2011), the most intense typhoon in 50 yr in Taiwan (Longshore 2009). Low tree mortality means that community structure was largely unaffected, which contrasts with patterns in many other regions subject to HES. In Puerto Rico's Luquillo Experimental Forest, 20% of the trees were uprooted or bole-snapped following category-three Hurricane Hugo (Walker 1991), in New England, 25–75% of the forests in the path of the category-three 1938 Hurricane incurred heavy tree mortality (Foster 1988), and in Queensland, most trees within 30 km of Cyclone Larry were broken or blown-down (Turton 2008). Variation in cyclone-induced tree mortality likely is related negatively to cyclone frequency. The return period of category three or greater cyclones in Taiwan is approximately one year. In contrast, the return period of cyclonic storms elsewhere is much greater: 60 yr for hurricanes such as Hugo in Puerto Rico (Walker 1991), 100–150 yr for HES such as the 1938 Hurricane in New England (Foster 1988), and 60 yr for storms such as Cyclone Larry in Queensland (Curran et al. 2008). Clearly, if typhoon-induced tree mortality in Taiwan were as high as in less frequently affected regions, forests would not persist.

At the FEF, streamwater chemistry exhibits high resilience. The elevated nitrate concentration in streamwater returned to the pre-typhoon baseline in only five days after Typhoon Herb (Wang et al. 1999, Lin et al. 2011), while it took approximately 500 d to return to pre-Hugo levels in the Luquillo Experimental Forest (McDowell 2001, McDowell et al. 2013). Due to the low tree mortality, most trees remain capable of taking up nutrients so that the elevated ion concentration in streamwater, associated of the leaching of nutrients in the foliage and soil during typhoon storms, quickly returns to pre-typhoon levels (Lin et al. 2011). Except after the record high four typhoons in 1994, canopy leaf area index (LAI) at FEF returned to pre-typhoon levels within one year, even after the most intense typhoons (e.g., the 1996 Typhoon Herb). Given the very high frequency of typhoons in Taiwan, the forest could not sustain its current structure, if nutrient concentration and LAI took more than one year to return to pre-typhoon levels.

Resistance and resilience are not necessarily mutually exclusive and may be interdependent both within the same component and between different aspects of a system. High community structure resistance, as a result of low tree mortality, facilitates the functional resilience (i.e., nutrient cycling) and the rapid rebuilding of affected ecosystem components (e.g., leaf area). Typhoon-induced defoliation is, in general, severe and contributes to low tree mortality because severely defoliated trees have a lower risk of being uprooted or snapped by high winds (Lin et al. 2011). In addition, trees that experience branch shearing by one storm are more resistant to branch shearing in subsequent storms.

Fish populations and communities in Taiwan are highly resistant and resilient to typhoon disturbance. The torrential rains brought by typhoons have major effects on streams such as altering stream channels, decreasing total pool area, and increasing total riffle area (Tew et al. 2002), but the effects on fish populations and communities are small and short-lived. A nine-year study of two fish species, *Onychostoma barbatula* and *Candidia barbata*, in response to three typhoons in a mountain stream indicates that typhoon effects on their abundances are minor despite the potential for habitat alteration (Chuang et al. 2008). A six-year study in a mountain stream of central Taiwan reported higher community resistance at upstream than downstream sites, and that the fish assemblage returned to its pre-typhoon state after a few months, indicating high resilience (Chen et al. 2004). The study suggested that both resistance and resilience were important in maintaining fish community structure over the long term (Chen et al. 2004). Even following the very intense Typhoon Herb (1996), most common cyprinids decreased in densities but returned to pre-typhoon levels after seventeen months, with only minor changes in fish community composition (Tew et al. 2002).

Social systems

For the social system, the number of households affected by power outages was greatest during Typhoon Soudelor (2015). Nearly 4.3 million households (52% of total) in Taiwan lost power during the typhoon period (6–10 August 2015). Repairs to the system occurred quickly: By noon on 10 August, only 2% of households still lacked power, and by 13 August, only 0.04% of households (~1400 homes) located in the most remote mountains had yet to recover (TPC 2015). This contrasts strongly with responses following Hurricane Katrina in the Gulf Coast. According to the US Department of Energy, after the landing of Hurricane Katrina, approximately 0.68 million households (63% of those in Louisiana) lost power by 3 September 2005, and by 16 September 2005, 24% of households remained out of power (USDE 2005). As with the ecological system, the much higher resilience in Taiwan can be attributed to the history of numerous devastating experiences over the past decades associated with typhoons. As a result of many years of such events, the Taiwan Power Company not only improved the transmission system to minimize typhoon impacts (increase resistance) but gained the experience to conduct repairs efficiently (increase resilience), a task that was further facilitated by a highly resistant and resilient road infrastructure (Lin and Kang 2012, Chang et al. 2013*b*). Heavy rainfall associated with typhoons inevitably damaged road systems, but the damage is typically minor at the island scale (i.e., highly resistant) and the repair often complete a few days after the storms stop (i.e., highly resilient). Typhoon Morakot brought approximately 3000 mm of rainfall to southern Taiwan in three days during 2009, with a maximum 24-h rainfall of 1623 mm (Fig. 2; Tsou et al. 2011), which is close to the world record (1825 mm in Aurere; Burt 2007). However, it only damaged approximately 600 km or 1.5% of the 40,000-km highway system in Taiwan (Teng et al. 2012). Repairs were mostly complete with two weeks with the most severely fragmented road (to the village buried by debris flows) reconstructed in 3 months.

In the agricultural sector, high winds and heavy rainfall associated with typhoons often cause major losses to crops, especially vegetables, as a result of flooding, which leads to price rises immediately following a typhoon (Fig. 5). Agriculture and Food Agency of the Council of Agriculture will investigate possible hoarding for profiteering when the prices are unusually high. In response to short supply, farmers plant fast-growing vegetables such as bok choy and water convolvulus, which can be harvested within 3–4 weeks to meet market demand. Even before the newly planted vegetables can be harvested, the Council of Agriculture often increases importation of vegetables or releases stored imported vegetables, and encourages people to purchase stem and root vegetables as substitutes for fruits and leafy vegetables that are more susceptible to typhoon-related damage. As a result, vegetable prices usually return to pre-typhoon levels in a matter of weeks (Fig. 5). Thus, very much like the ecological system, typhoon disturbance

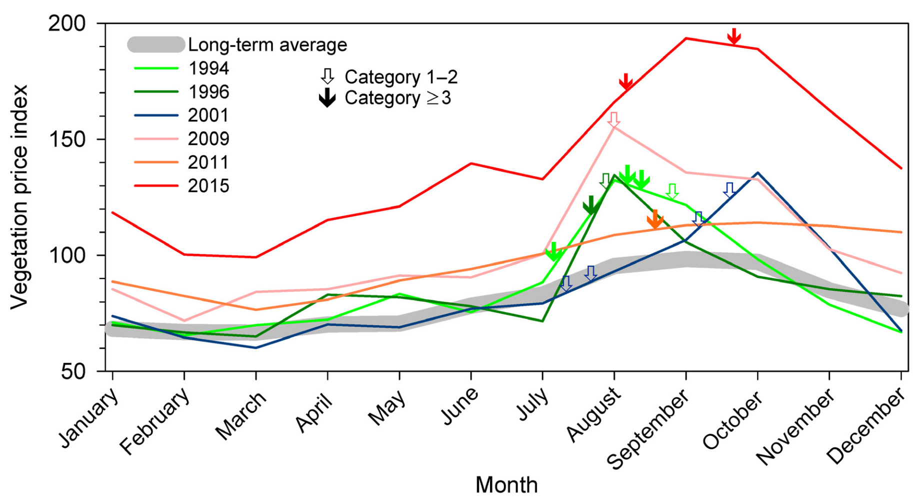


Fig. 5. Monthly vegetable price index during the six years with typhoon tracks listed in Fig. 2. Long-term average based on data for all years from 1994 to 2015. Data from National Statistics of Taiwan (http://www.stat.gov.tw/mp.asp?mp=4).

causes major fluctuations to the social system, but people are knowledgeable of these events, and Taiwan's social system is highly adapted to frequent shocks associated with HES.

Although the power system and vegetable prices show high resilience to typhoon disturbance, the drainage system in the coastal plains is both resistant and resilient to typhoon disturbance. Following Typhoon Morakot, that brought nearly 3000 mm of rain, approximately 400 km^2 of southern Taiwan experienced flooding, but the floods retreated after four days despite damage to the drainage system, with 45.8 km (or 4%) of river embankments ruined according to the Water Resource Agency (Yang 2010). Despite extremely high rainfall, the area flooded was small and the retreat was quick, reflecting high resistance and resilience of the drainage system. Again, this is in striking contrast to flooding in Louisiana following Hurricane Katrina, during which flooding lasted for more than one month in New Orleans although in both coastal Louisiana and southern Taiwan flooded areas are flat.

Following Typhoon Morakot, a National Flooding Control meeting was held (11 October 2009) to strengthen the drainage system; this reflects the responsiveness of the social system to the new record of typhoon rainfall. The government of Taiwan proposed approximately USD 25 billion for flood control, and a budget of USD 20 billion was approved by the Taiwan Congress in 2013. The budget included construction of high-efficiency and high-capacity drainage systems. The substantial investment in the long, elevated highway bridges over wide floodplains commonly seen in Taiwan is an adaptive response to frequent flooding associated with typhoons.

Not all drainage systems are well adapted to typhoon disturbance. Using constructed wetlands to remove water pollutants is relatively new in Taiwan. A study on efficiency of pollutant removal indicated that constructed urban wetlands in the Danshui River Basin of northern Taiwan removed 64.3% BOD (biological oxygen demand), 98.9% NH_4–N, and 39.5% total-P before Typhoon Krosa (2005), but performance diminished after Typhoon Morakot to 37.7% BOD, 35.1% NH_4–N, and 31.8% total-P, in part because of damage to the constructed wetland system (Ko et al. 2010). The study suggests that high-flow bypass systems should be used to protect constructed wetlands from typhoon storms. Another study reported that the pollutant removal efficiency of the damaged constructed wetlands could be restored by re-constructing urban wetlands (Fan et al. 2009). The power system, the road system, the large drainage infrastructure, and the agriculture system all have been affected by typhoons for many decades so that resistance and resilience have been established through adaptive responses over the past several decades. In contrast, constructed wetland systems are new and are likely still undergoing a typhoon-induced strategic redesign to enhance resistance and resilience to frequent typhoon disturbance.

In many ways, the social–ecological systems of Taiwan are well adapted to typhoon disturbance. However, the combination of typhoons and other types of disturbances, such as earthquakes and droughts, have the potential to reduce resistance and resilience and lead to unexpected changes. For example, the moment magnitude scale (Mw) 7.6 earthquake of 21 September 1999 shook the land, loosening soils and making the island more vulnerable to subsequent storms. Even more than a decade later, many of the debris flows during typhoon periods continue to be at least partially attributed to the loosened soils caused by the earthquake (Lin et al. 2006*a*). The earthquake lowered critical thresholds of precipitation (quantity or intensity) needed to trigger debris flows, imposing new challenges to the management of such coupled systems. With the recognition of the inevitability of unexpected damages caused by typhoons, Taiwan's "National Fire Agency" was replaced with "National Disaster Prevention and Protection Agency" following typhoon Morakot (Wen et al. 2014). The amendment of the "Disaster Prevention and Protection Act" to improve the disaster management system and the movement of the "Central Disaster Prevention and Response Council" and "National Disaster Prevention and Response Committee" to "Office of Disaster Management" represent some of the adaptations of the social system to frequent and sometimes catastrophic typhoon disturbance (Wen et al. 2014).

HES and System Dynamics

Ecosystems

Characterizing the departure from and return to pre-disturbance state is essential in studies of disturbance. Although it is conceptually straightforward to study resilience (i.e., the time required for an ecosystem to return to pre-disturbance conditions, or recovery) for systems that experience infrequent disturbance events, the concept of "recovery" is pushed to its limits in regions such as Taiwan, where disturbance events are quite frequent. Returning to pre-disturbance conditions is possible when the time required for the return with respect to some environmental attributes (e.g., litterfall, LAI, productivity, stream water chemistry) is shorter than the interval between consecutive disturbance events (Fig. 6a). However, for systems that experience annual typhoons of a variety of intensities, the dynamics are more complex and challenge the notion of resilience from conceptual and methodological perspectives. For example, the system may have recovered from the most recent typhoon that caused only leaf loss, but not from a more intense earlier typhoon that caused tree bole and limb breakage (Fig. 6b). In northeastern Taiwan, canopy LAI usually returns to pre-typhoon levels within a year, but it took 10 yr following the three category-three typhoons in 1994 (Lin et al. 2011).

In a highly dynamic system, the reference state for quantifying resilience may be unknown or be inferred inaccurately. For example, if the LAI prior to the 1994 typhoon season had not been measured, our understanding of LAI dynamics between 1995 and 2005 at FEF in northeastern Taiwan might be very different (and incorrect). The temporal pattern observed in that case would likely be interpreted as a strong growth trend and erroneously attributed to other drivers, when in fact LAI was recovering from multiple typhoon disturbances in 1994 (Fig. 7). In addition, other disturbances, such as drought and extreme spring low temperature, may come into play between typhoons and make it even more complicated to define the reference state. Maximum gust wind of and rainfall associated with landfall typhoons are increasing in Taiwan (Fig. 3), as such the dynamics of the system might not be easily projected from the patterns in the past, given a changing disturbance regime.

Social systems

While the resilience of natural ecosystems largely depends on internal processes shaped by

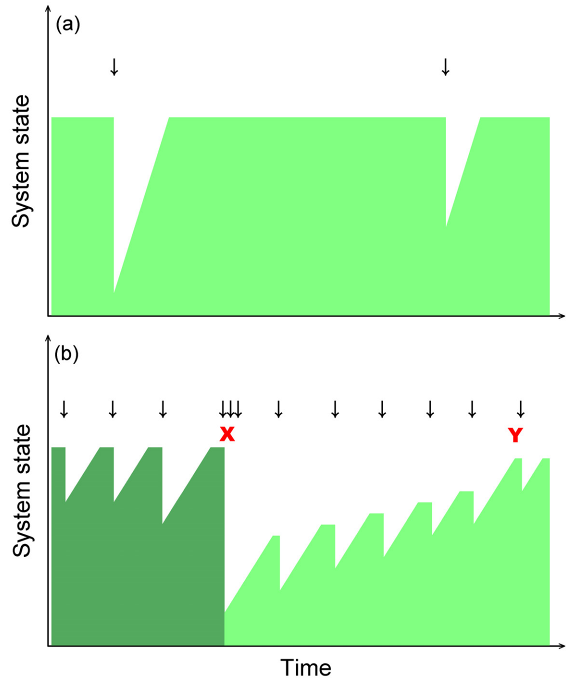


Fig. 6. Representation of resistance and resilience in ecosystems experiencing high-energy storms (HES) of different frequencies and intensities. The departure from the pre-disturbance state represents ecosystem resistance, and the time length of the departure interval represents ecosystem resilience. Each arrow represents a HES. Panel (a) illustrates an ecosystem with infrequent HES, in which the time required for the system to return to pre-disturbance state in some important ecosystem properties (e.g., leaf area index, NPP, nutrient balance) is considerably shorter than the storm return interval. Panel (b) illustrates an ecosystem with frequent moderate-intensity HES and occasional an extreme HES that create effects not seen in less intense storms (e.g., extremely high defoliation), with longer recovery times upon which the dynamics of more moderate events is superimposed. The regular HES are not necessarily less intense than those in systems of panel (a). Extreme HES could be HES of extreme intensity or multiple high-intensity HES. Note that without information at point X in panel (b), the ecosystem may be inferred as in a growing (or accumulating) stage at the time between point X and Y, when in fact it is in the process of returning to the state at point X. This happens when the monitoring period is too short to include extreme HES and the time required for the return to the state prior to the extreme HES is long.

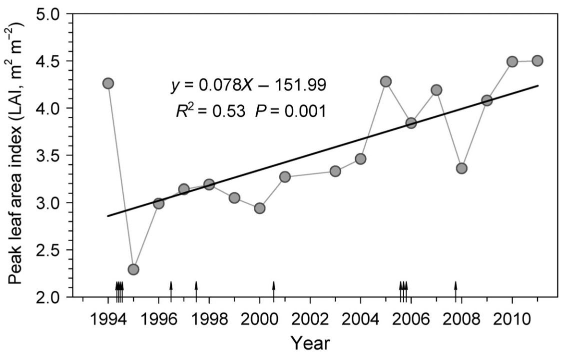


Fig. 7. Temporal patterns of annual peak leaf area index (LAI) at Fushan Experimental Forest (FEF) between 1994 and 2011 (adapted from Lin et al. 2011). Arrows indicate category three or greater typhoons that affected FEF.

the long-term interaction with annual typhoons, resilience of social systems depends on human interventions. For example, the rapid recovery (i.e., high resilience) of vegetable prices is the result of both the planting of fast-growing vegetables and the importation of vegetables from other countries. The small proportion of highway and road systems damaged and the rapid reconstruction of highway and road systems following even the most catastrophic typhoons depended on the establishment of highly efficient and effective construction teams. Thus, resilience requires actions taken both within the system (i.e., planting fast-growing vegetables) and outside the system (i.e., importation). If typhoon disturbance becomes more frequent, more rapid responses by farmers and related government sectors are key to maintaining the resistance and resilience of social systems.

Unlike the difficulty in defining the reference state of ecosystems in response to typhoon, except for multiple typhoons in one year, the reference state of vegetable price, highway systems, and many other social components is clear because social systems are almost always fully recovered before the next typhoon season. Such quick recovery is necessary for social systems that experience annual HES to maintain functioning. However, there is one important exception to this. When effects are severe such as the burial of Shaolin village by debris flows associated with Typhoon Morakot, the village was not rebuilt in the same place, but left for natural succession to take place, while the survivors migrated to a new location. It is not clear if the site will ever be reinhabited by humans in the near future, as the site is still vulnerable to debris flows.

Toward Mitigation of Typhoon Effects

A new cyclone classification is required

Enhancing adaptations of social–ecological systems to typhoons may be considered the most effective manner for mitigating typhoon effects. However, we argue that improvements in the cyclone classification and warning system should be of the highest priority because accurate warning is a prerequisite for prevention measures, including evacuation from areas with high risk of debris flow and enhancement of wind protection for households and animal stocks.

Typhoons in Taiwan are classified into three categories of intensity based on the speed of sustained winds, similar to the Saffir-Simpson Hurricane Scale. Although different countries (e.g., Japan, Taiwan, and Australia) have slightly different classification systems, they are all mainly based on wind speed with some considerations on air pressure and storm surge. A wind speed-based classification is predicated on the assumption that tropical cyclones with higher winds have greater potential to affect ecosystems (Bell et al. 2000, Powell and Reinhold 2007). Based on topographic wind exposure, Boose et al. (2004) developed a meteorological model, which successfully reconstructed the effects of hurricanes on the Luquillo Experimental Forest. However, Typhoon Herb, a category-three storm, led to 52 causalities in central Taiwan, while Typhoon Morakot, a category-two storm, led to 500 causalities in southern Taiwan. Importantly, these causalities were caused by debris flow associated with heavy rainfall, rather than with high winds. Similarly, the extensive effects on the social system caused by category-two Hurricane Floyd (1999) in the United States were due to extensive flooding rather than to high winds (Atalah and Bosart 2003). This illustrates the need to include rainfall intensity into a classification and warning system for HES (Chang et al. 2013*a*). Thus, we propose that an effective warning system must include precipitation intensity. Such a system is particularly important in regions with rough topography in which wind velocity decreases but precipitation increases from reef to ridge.

A non-equilibrium perspective is critical

In addition to improving the classification or warning system, we also argue that a conceptual shift about the social–ecological systems that moves from an equilibrium to a non-equilibrium perspective is important to the management of systems that are subject to frequent HES. The 20-yr record of LAI at the FEF indicates ecosystems are not in an equilibrium state. Perhaps in regions with HES as frequent as in Taiwan, the system should be understood with a non-equilibrium perspective because the system is repeatedly affected by typhoon disturbance, which itself is changing through time (e.g., increases in frequency). As pointed out by Mori (2011), a non-equilibrium perspective recognizes "the potential of episodic large changes caused by typhoons and other natural disturbances." Thus "rather than management grounded on the equilibrium view that is trying to completely exclude the possibilities and outcomes of large disturbances" (Mori 2011), a non-equilibrium perspective of ecosystem management recognizes that disturbance is not necessarily a disaster. Rather it is inherent to the structure and function of the system. Therefore, one of the keys in managing such highly dynamic systems is to identify the legacies and processes that contribute to the resistance and resilience of the system.

Increasing discussion between social and natural scientists is vital

Unlike the natural system in Taiwan, which has developed under frequent typhoon disturbance for thousands of hundreds of years, the rapidly changing social system has had relatively recent contact with typhoons. Nonetheless, experience over the past several decades has allowed Taiwan to improve the resistance and resilience of the social systems. However, new elements of the social system, such as the artificial wetlands, are still undergoing the adaptive learning process. Typhoon disturbance must be taken into consideration in the design of elements in the social system as a way to maintain and promote resistance and resilience. Much can be learned from ecosystems to improve the resistance and resilience of social systems. For example, the linkage between leaf resilience and the resistance of boles and community composition (Lin et al. 2011) is crucial to maintaining the current structure and function of the forest ecosystems in Taiwan. The incorporation of such connections into the design or management of social systems should be of high priority. On the other hand, human interventions, such as the formation of mission-oriented government agencies for stabilization of vegetable prices and post-typhoon reconstruction, are key to the resistance and resilience of social systems. In this regard, management of natural systems could benefit from the accomplishments of the social systems. Thus, increasing dialogue between social and biophysical scientists could be an important step toward an integrated thinking and learning models that are required to effectively mitigate the impact of HES.

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