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Perspectives

Disease epidemics: lessons for resilience in an increasingly connected world

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In public health, the term resilience often refers to the personality traits that individuals possess which help them endure and recover from stressors. However, resilience as a system characteristic, especially in regards to complex social-ecological systems, can be informative for public health at scales larger than the individual. Acute shocks to systems occur against a background of existing conditions, which are crucial determinants of the eventual public health outcomes of those shocks, and in the context of complex dependencies among and between ecological and societal elements. Many components of a system's baseline condition are chronic public health concerns themselves and diminish the capacity of the system to perform in the face of acute shocks. The emerging field of resilience management is concerned with holistically assessing and improving a system's ability to prepare for and absorb disruption, and then recover and adapt across physical, information, environmental and social domains. Integrating resilience considerations into current risk- and evidence-based approaches to disease control and prevention[1] can move public health efforts toward more proactive and comprehensive solutions for protecting and improving the health of communities. Here, we look to the case of the Black Death as an illustrative case of a dramatic transformation in human history, an acute shock to a system that was underlain by chronic social maladies, to derive lessons about resilience management for public health in contemporary systems.

The Black Death was the first and most devastating outbreak of what is commonly referred to as the Second Pandemic of plague. In just a few years in the mid-14th century, the pandemic killed an estimated 30–60% of affected populations.[2] Recent paleodemographic research on the effects of the Black Death in London has revealed evidence that survivorship increased and age-specific mortality rates decreased in the 200 years following the epidemic. This suggests underlying health improvements in the post-Black Death population compared with the pre-Black Death population.[3] In speculating about the factors that led to a healthier population, we look to research using a cemetery comprised entirely of individuals who died during the Black Death in London that examined whether the disease killed indiscriminately, as most people have assumed, or if people varied in their risks of dying during the epidemic. Analysis of skeletal markers of physiological stress (such as those shown in Fig. 1), which have been shown under conditions of normal, non-epidemic medieval mortality to be associated with elevated risks of mortality, revealed that people of all ages who were already in poor health before the Black Death subsequently faced higher risks of death during the epidemic than their healthier peers.[4,5] That is, the Black Death was selective with respect to frailty (an individual's risk of death relative to other members of the population).[6] Such selective mortality might have powerfully affected health and demography in the aftermath of the Black Death, as analyses of pre- and post-Black Death skeletal samples from London reveal improvements in survivorship and risk of mortality and, by inference, health following the Black Death compared with conditions before the epidemic.

Given that people of all ages, including reproductive-aged individuals, with relatively high frailty were more likely to die during the Black Death than their age peers with lower frailty, the epidemic might have affected genetic variation with respect to disease susceptibility or immune competence and thus acted to reduce average levels of frailty in the surviving population. Alternatively, the Black Death might have affected

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Fig. 1 Linear enamel hypoplasia on a permanent canine. These stress markers present as linear grooves along the surface of a tooth and represent interruptions in enamel formation during childhood in response to various physiological stressors.

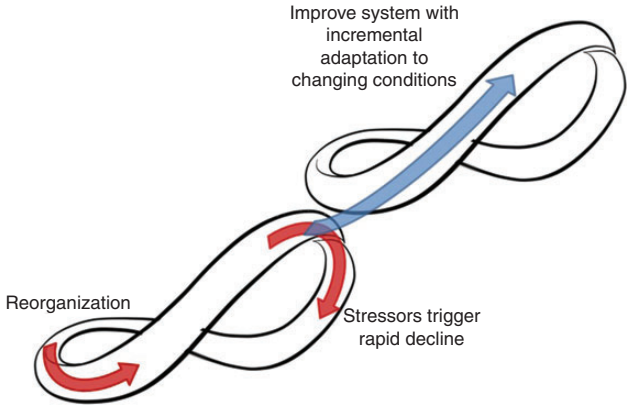

Fig. 2 Adaptive cycles within a simplified panarchy (nested set of adaptive cycles). Axes are space and time, and reorganization involves both structure and function. Gunderson and Holling theorize that the structure of social-ecological systems is hierarchical, composed of scale-specific adaptive cycles of renewal and collapse. The collapse at a single scale affects lower level organization, and given synchrony of collapse within multiple adaptive cycles collapse can scale up and affect larger structures and processes. Collapse provides opportunity for humanity—it is here than human intervention can transform the reorganization stage of the adaptive cycle 8 to create more desirable states. A system that has matured, seemingly to an equilibrium steady state, can undergo rapid and dramatic change if thresholds for stress are exceeded, triggering a collapse in which connections are broken and capital is released. Adaptation comes about when dominant schemes are destroyed and a system can organize into a new stable state, or conceivably add larger scale structure to the system. By the same logic, the Black Death-induced depopulation triggered rapid decline of social and economic structures in medieval Europe, following the arrows on the lower left loop. Alternatively, policies can prompt reorganization and create windows of opportunity for adaptation, so improvement is not contingent on adverse events. Conceptually, a system could follow the arrows onto the upper right loop, moving from a mature state to a stage of reorganization and growth without collapse.

health via substantial improvements in standards of living that occurred as a result of massive depopulation. After the Black Death, wages improved dramatically while prices for food, goods and housing fell.[7] Improvements in diet after the Black Death might have reduced average levels of frailty in the population, perhaps more than any other factor associated with improvements in standards of living. In terms of resilience lessons, however, we should examine how the massive depopulation event led to or accelerated numerous economic, political and social changes. The Black Death marked a turning point in Late Medieval Europe[8] by creating such a profound disturbance that, for example, it 'forced the economy to transition from low-level equilibrium trap to higher growth path'[2] and may have greatly influenced the trajectory of many Western economies.[9]

Dramatic transformations in society, triggered by the Black Death, may have occurred because progressive change had not been allowed or could not emerge because of intrinsic inertia in the system. Prior to the Black Death in Europe, economies were stagnating, feudalism prevailed and with it, according to Epstein,[8] there was low investment in improving agriculture, little innovation, an absence of competitive markets, food distribution limitations, peasantry that were pushed to their individual physiological limits and jurisdictions that were isolated from each other. The Black Death occurred at a time of frequent, devastating famines. Population growth and simultaneous increases in taxes, rent and grain prices in the 12th–13th centuries created stark social inequalities,[10–12] particularly with respect to food availability, in the pre-Black Death population. Famine might have increased frailty, at least for people of lower socioeconomic status. Hazard and survival analysis of skeletal samples from London reveal decreased survivorship and increased risks of mortality and, by inference, declines in health in 13th century London compared with 11–12th century.[13] Declines in health concomitant with increasing populations and population connectivity via regional commerce before the Black Death might have contributed to extraordinarily high mortality levels during the epidemic.

Juxtaposing the pre-Black Death social and economic structures to those that emerged post-Black Death lends itself to thinking about the epidemic in terms of resilience. Panarchy, a theory derived from the study of complex social-ecological systems, describes the dynamics and resilience of a complex system as a nested set of 'adaptive cycles'.[14] Within an adaptive cycle, the response to stresses that exceed the system's thresholds is not usually smooth or gradual but instead rapid and dramatic (Fig. 2). According to the theory, collapse is an inevitable

consequence of increasing connectivity, capital, specialization and intensification at a single scale within a system, and the cycle of destruction and renewal has been termed an adaptive cycle.[15] Resilience, in this use, is a measure of the amount of perturbation a system can take without collapse. System collapse may be followed by reorganization around the same initial sets of processes and structures, or around a new set of processes and structures leading to a fundamentally different configuration of the original system, and can add to, or delete, scales of structure.[16] Panarchy envisions the organization of complex social-ecological systems as a nested set of adaptive cycles, each occurring at discrete scales. Cycles of collapse and renewal are scale specific; necessarily smaller faster scales are always affected by collapse at larger scales; sometime collapse at a smaller scale can scale up and affect larger scale processes and structures.[15] Resilience is fundamentally different from stability and equilibrium-based approaches to understanding system dynamics in that it enables a system to maintain functioning by reorganizing and modifying in response to new conditions and, in some cases, by moving to an different stable state.[17]

From the perspective of Panarchy, perhaps Late Medieval Europe was 'predisposed' for a catastrophe and suffered an inevitable demographic decline, with the Black Death as a catalyst. Conceivably, entrenched social and economic systems and dependencies created rigidity and vulnerabilities that were exploited when the Black Death killed large portions of populations across the continent. Reorganization in Europe following the Black Death resulted in new structures and functions: food prices were reduced, serfdom, which had previously prevented peasants from migrating in search of better opportunities, broke down, commercialization was stimulated, and competitive markets emerged.[7,18] In essence, socioeconomic systems were adapting to change—notably, the loss of a large portion of its labor force—and responding to opportunities presented by released capital.

While collapse might be the natural and inevitable way that social-ecological systems transform and move through adaptive cycles, the process of reorganization and reformation of Late Medieval European society into something very different from what existed before came at a huge cost and is an untenable, passive and dangerous way to change. From an ecological view of resilience, we can learn, however, that breaking down persistent connections can create opportunities for improvement and novelty. In fact, this idea is already surfacing in current public health conversations, where there is growing recognition that persistent poverty, mass incarceration, institutional racism and other chronic social issues diminish communities' ability to absorb the impacts of adverse events and agility to adapt in the face of change. Contemporary societies, in many ways, still rely on opportunities presented by disaster to improve, but it is possible to orchestrate incremental changes and minimize the disruption of changing conditions (Fig. 2).

The emerging field of resilience management, focusing on both ways to enhance the resilience of desirable systems and on eroding resilience and fostering transformation when systems are in undesirable states, could provide a means for identifying points of weakness, support efforts to improve 'the ability to adapt to change, to be able to respond in a flexible way to uncertainty and surprises' and create opportunities for change.[9] A resilience assessment addresses all aspects of a community, including health and medical care, as well as physical infrastructure, social structure and capabilities for dissemination of critical information. The performance of the entire system in preparing for, absorbing, recovering and adapting to diseases and other threats can be quantified. Approaches such as the resilience matrix[19] can help reveal which key variables control system-level responses to stress and how we can leverage opportunities to manage them.[20] The matrix approach to resilience assessment entails first, identifying the critical functionalities of a system in question, which would ideally be maintained or quickly restored following an adverse event. Assessment of each critical function is then made based on how it is anticipated to perform through time; before, during and following an event.

The transformation of medieval Europe following the Black Death provides a precautionary tale for the Anthropocene: failure to manage the ever-increasing connections of our modern world can leave us vulnerable to undesired transformations. Particularly, given the uncertainty about what, when and where contemporary risks will be posed to community health, resilience management can help guide work to manage communities' baseline condition; to proactively prepare for shocks and maintain communities that can respond and adapt in the aftermath of shocks.

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