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Community Capitals Framework for Linking Buildings and Organizations for Enhancing Community Resilience through the Built Environment

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Abstract: The goal of this paper is to define a quantitative measurement system capable of capturing multiple dimensions of a community impacted by disaster. The multiple dimensions of a community are defined here as the seven community capitals inherent to any community, namely, financial, political, social, human, cultural, natural, and built capitals. A two-pronged approach is proposed, where one prong relates organizations to community capitals using a novel scoring system aligned with the definition of each community capital, and the other prong relates building-damage consequences to the community capitals, including number of damaged buildings for built capital, household dislocation for social capital, morbidity rates for human capital, accessibility changes for political capital, and repair costs for financial capital. The framework is exemplified on a virtual community, Centerville, under an earthquake scenario. The example demonstrates that the proposed approach for quantifying capitals provides useful measures of disaster impacts and can readily inform risk-based decision making.
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Introduction

This work is motivated by the current momentum concentrated on transitioning out of a resistance-based strategy to design building systems, and into a strategy that provides community resilience through holistic integration of the technical, organizational, social, and economic systems imperative to a community's functionality. Community resilience—understood here as a theory, a set of capacities, and a strategy (Norris et al. 2008) "to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (PPD 2013)—can be sought to produce major cost-savings, sustain quality of life, and begin to rectify the long-standing problems of the current approach that limits itself to considering the structural integrity of one building at a time and providing life safety to building occupants during design-level events. Seminal research points to community resilience approaches to designing infrastructure that possess redundancy, resourcefulness, rapidity, and robustness in the design of systems (Bruneau et al. 2003), networked capacities of the seven community capitals defined in Table 1 (Ritchie and Gill 2011; NIST 2015), and integration of resistance, adaptive capacity, and transformability in response to disturbances (Walker et al. 2004; Folke 2006; Chapin et al. 2010) through incorporating functionality, planned recovery, and considering the people and organizations that use and operate infrastructure to drive innovation. Widespread failure to adopt community resilience approaches to building design is a major cause of extraordinary government spending and recovery periods that last upwards of five to 10 years, particularly for communities, businesses, and households with the greatest needs.

This paper presents a framework for measuring community resilience through considering a holistic view of a community that includes the built environment, and its social and economic systems. The framework focuses on building systems, and how said portion of the built capital supports social, human, political, financial, cultural, and natural capitals. The framework provides three major contributions to the community resilience literature by: (1) providing a concise yet comprehensive literature review on each of the community capitals and their intersection; (2) combining what is already established in the literature in terms of postdisaster human and building loss estimations; and (3) combining the community capitals quantitatively into a single, executable framework. The proposed framework is based on the assumption that different building occupancy types—through their organizations—generate different community capitals and thus provide a system to measure this generation. For example, religious organizations and museums generate cultural capital through the programming they offer. Additionally, religious organizations and physical fitness centers generate social capital through their membership functions and events. Schools and healthcare facilities generate human capital through increasing knowledge and health of community members. Retail shops and restaurants facilitate financial capital through offering places of employment and providing a means for local commerce.

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Table 1. Definitions of seven community capitals

Community capital	Definitions
Built capital	Buildings and infrastructure systems within a community
Social capital	Social networks, associations, and the trust they generate among groups and individuals within the community
Human capital	Knowledge, skills, health, and physical ability of community members
Political capital	The ability to engage external entities in efforts to achieve goals and the ability/power to access and influence the distribution of resources
Financial capital	Available financial savings, income, investments, and credit at the community-level that is instantly accessible
Cultural capital	Language, symbols, mannerisms, attitudes, competencies, and orientations of local community members/groups
Natural capital	Resources, such as air, land, water, minerals, oil, and the overall stability of ecosystems

Source: Adapted from Ritchie and Gill (2011).

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These relationships, albeit proxy measures of the community capitals, are described for a selection of organization types, and illustrated using a virtual community; outputs are presented in the form of a dashboard for risk-based decision-making.

The seven community capitals, presented in Table 1, are not self-governing. For example, financial capital in a community is partly dependent on knowledge and skills possessed by the population (human capital), the networks of people in and outside of the community (social capital), and their influence on distribution of resources within and outside the community (political capital), and being influenced by natural resources (natural capital) in the community, such as beachfront property, mountain views, port access, or coal mines (Hanushek 2013; McCrea 2014; Pickett et al. 2004; Donoghue and Sturtevant 2007; Emery and Flora 2006). Similarly, built capital will be higher in communities with higher human, political, and financial capitals. The following section introduces the relationships used herin in the context of the existing literature. The proposed framework is then introduced, followed by descriptions of the organization-based and consequence-based measurements, and finally the framework is exemplified on a virtual community.

Background on Community Capitals and Their Intersectionality

Here, the term capital is used to describe an asset; seven categories of assets inherent to communities are reviewed herein, where each community capital has individual and collective influence on community disaster resilience. The literature on individual capital influence on community disaster resilience is significant for built and social capitals, whereas coverage of the other five capitals and deep understanding of the intersectionality of capitals is limited and requires further research. What is known about individual influences on community disaster resilience and intersectionality, and how it was used in the development of the community-level measurements in this study, is reviewed and discussed here.

Built Capital

Built capital refers to the built environment. Whereas solely buildings are modeled in this study, built capital also includes transportation, telecommunication, water, wastewater, power generation, and distribution systems, and the like. The purpose of built capital is to serve human needs, wants, values, and to mediate or change the overall environment for societal comfort and well-being (Bartuska 2007). Truly, the built capital in a community is, or should be, designed to support the other six capitals. When elements of the built capital are disrupted or lost, e.g., power outages or building collapse, there are important implications and subsequent disruptions to human capital through deaths, injuries, and lost education time; to social capital through disrupted social networks, shared spaces, and offerings of community events; to financial capital through the cost of cleaning up and repairing damage, and lost employment and revenue; to cultural capital if historic monuments or cultural spaces and buildings are destroyed or if rebuilding expands to reservations or spaces of historic significance; to natural capital through pollution caused by damage and repair processes, and lost natural capital potential through expansion in green areas during rebuilding, for example. Importantly, when elements of the built capital are disrupted or lost, historically underserved community members and those with lower political, financial, and social capitals can be differentially impacted; thus, built capital preservation and natural capital conservation have important implications towards social equity and environmental justice, and community disaster resilience (Logan and Guikema 2020; Logan et al. 2021).

Postdisaster studies demonstrate a need for buildings and other physical infrastructure to stay functional in an effort to preserve community functioning after a disruptive event (McAllister 2015; NIST 2016; Sattar et al. 2018; Koliou et al. 2020). Disaster research suggests that built capital is generated through the application of financial, human, cultural, and social capital (Goodman 2003; Flora et al. 2004; Ungar 2011). For example, Brugmann (2009) describes how cities with no planning may reach high urban density, but the overall result is often inadequate.

Take the case of Houston and 2017 Hurricane Harvey. Houston's population grew enormously since 2005 Hurricane Katrina. The lack of land-use planning in Houston led to disastrous consequences from Hurricane Harvey, with extensive and widespread neighborhood flooding that planners say could have been avoided (Sebastian et al. 2017). When urban density grows without planning, people with insufficient financial capital become economically burdened, without sufficient political capital, people can be pushed out through gentrification, and may be left to live in overcrowded and unhealthy buildings. The interaction of human and financial capital with built capital, accounting for the natural capital in a community, is imperative for resilience.

A typical action to mitigate disasters is to strengthen the physical infrastructure; however, doing so will not fully eliminate hazard vulnerability (Sutley et al. 2017). Urbanists suggest that broadening housing, business, public, and private sectors would create a shared advantage and improve community resilience through built capital (Alexiou 2006). Creating places of mutual interaction and services promotes participation, shared values, and a sense of trust that leads to social capital development (Fedders 2018). Therefore, hardening buildings that produce these specific capitals, in this case social capital, and benefit other capitals, will likely ameliorate the resilience of the community.

Such approaches of creating places of mutual interaction must be equitably distributed across a community. Too often, the interaction of built, human, social, cultural, and natural capitals is not

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appropriately taken into consideration during development. Individuals and households with the highest social vulnerability often also live and work in outdated or structurally deficient buildings positioned in more hazardous areas, such as floodplains (Sutley et al. 2020; van de Lindt et al. 2020). Wealthier neighborhoods often have greater access to schools, hospitals, and grocery stores. This intersection of social and physical vulnerability carries over post-disaster, where we see other infrastructure systems are not maintained or restored at the same rates (Mitsova et al. 2018; Coleman et al. 2020). Consequences of a disparately designed and maintained physical infrastructure result in differential built, human, financial, and political capital; such inequity inhibits trust across a community and subsequently, social capital. Outside of a disaster context, disparately designed and maintained physical infrastructure, as well as its placement has led to historical legacies of differential access, environmental injustice, and systemic racism (Dwyer 2007; Martin and Lewis 2019).

Social Capital

Social capital refers to the trust generated among groups and individuals within the community as a result of social networks and associations (Ritchie and Gill 2011). Unlike built and human capitals, social capital does not simply exist; social capital is only generated in the interactions between individuals and among groups. Social capital requires action to be established (Tierney 2014). It is, therefore, one of the most crucial community capitals that is closely linked to and overlaps with other community capitals, including human, political, and cultural capitals. Fothergill and Peek (2004) describe that people with lower socioeconomic status, those living in extreme poverty and with higher illiteracy rates, and those living in physical isolation in rural communities more often fear and distrust government officicals, which has important implications for warning communication, and making recovery resources accessible in a disaster context, as well as pre-disaster social capital.

Woolcock and Narayan (2000) articulates three types of social capital: bonding, bridging, and linking. Strong, close, familial-type relationships form *bonding social capital* where each person feels closely connected with trust and access to decision-making power in the relationship. Bonding relationships can be formed by those living in the same home as one another. *Bridging social capital* refers to connections across divides, such as race and class, and connect individuals with authorities and people with power and resources. Bridging relationships can be formed through religious or education-based organizations, amongst others. Lastly, relationships providing *linking social capital* are often established through one or more common interest, such as co-workers or members of the same municipal sports league. Thus, organizations with multiple employees, or that offer memberships may produce social capital. In general, organizations and intentionally-designed building spaces that bring people together may facilitate the growth of formal and informal relationships, and thereby social capital (Glanz 2011; Carpenter 2013). A person's relationships through their bonding, bridging, and linking networks can provide them with more or less access to resources, information, decision-making capability, and relative power, i.e., political capital, and is highly correlated with individual human and financial capital, which aggregates, respectively, for a whole community (Aldrich 2012). When social networks are disrupted during a disaster, important social capital can be temporarily or permanently lost, which can greatly slow down recovery processes for individuals (Erikson 1978).

Chamlee-Wright and Storr (2009), in their discussion of how religious organization supports community recovery after a disaster, reference a local church as being "the hub around which spiritual, social, and commercial life evolved" (Chamlee-Wright and Storr 2009, p. 433). These types of connections are qualitative in nature, and can prove difficult to justly measure. However, similar to physical and economic capital, social capital operates "as a public good . . . that is, a resource which provides nonexludable benefits, so that all residents of a high social capital neighborhood enjoy its positive side effects" (Aldrich 2011a, p. 3). Social capital is increased through relationship building and increased interaction, which can be achieved in many ways including through community members having set roles and responsibilities within organizations through leadership and teamwork (Norris et al. 2008). The built environment thus can be designed to foster social networks through walkable and mixed-use neighborhoods, for example (Glanz 2011). Carpenter (2013) used this notion to create a resilience measurement, adopting six built environment variables affecting social capital, including land use mix, housing density, intersection density, social gather place density, parks and open space density, and historical site density. Collectively these six variables capture probability of social encounters, places that promote social gather, and places that increase place attachment for community members. Fedders (2018) further builds on the Carpenter (2013) measurement through the development of three indices, namely organization social capital index, building social capital index, and critical infrastructure interdependency index. The purpose of the indices was to measure the ability of organizations to produce social capital, and capture the interdependent relationship between organizations producing the most social capital and those organizations commonly referred to as critial. Libraries, community centers, churches, hospitals, and schools resulted in the highest social capital production in the Fedders (2018) framework.

Of note, social vulnerability has been extensively studied and quantified in the disaster literature, and refers to the characteristics of an individual or group that make them more susceptible to harm. Individuals and groups with higher social vulnerability often have lower social, human, political, and financial capital, however,

Human Capital

Human capital has one of the most substantial ties to each of the other capitals because it is community members who get things done and the reason communities exist. Ideas, attitudes, willingness to participate and the power of working together is how human capital affects a community. Mixing individual capacities and identifying, using, and combining resources can benefit both the individual and the community. Human capital is also developed through other community capitals such as social capital (Coleman 1988) and leads to the development of financial and political capital (Pelinescu 2015).

Knowledge and skills of community members facilitate the ability to think in new ways and are also the basis of developing leaders in the community. Therefore, schools and other organizations that provide training or educational programs, businesses that provide skill development for employees or customers, or civic processes that incorporate community engagement can increase human capital in a community. Health and physical ability of community members are important factors contributing to human capital; psychological and physical well-being are vital to productive activities and actions in the event of a disaster. Thus, human capital is equipped and maintained by physical and institutional infrastructures, including healthcare systems and recreation-based organizations (Folds and Thompson 2013). Access to healthcare, education, and employment form the core of social sustainability and

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resilience, along with the beliefs, desires, and intents that engage individuals to participate in those systems in productive ways (e.g., cultural and social capitals). Enhancing a community's resilience must then address not only the physical infrastructure but also the human capital redevelopment (Mcdermott et al. 2016).

Political Capital

Political capital connects community development with government resources and private investment. It reflects the population's capacity to express themselves and to participate as agents in their community (Goodwin 2003). It is also the community's ability to access public resources or impact the rules and regulations that affect its own day to day functioning, which, in a democracy, is often mediated through elected leaders and officials (Vidich and Bensman 1968). Social systems of trusting relationships between people who are interacting with formal or established power or authorities such as government and local organizations form this type of political capital (Szreter and Woolcock 2004). Furthermore, faith-based organizations stimulate local activity, increase interactions, and facilitate organized activity, in times of normalcy and serve as a resource distribution hub during times of disaster. Collectively these actions may enhance resource networks in a community. Similarly, education-based organizations provide resources, such as emergency shelters, after disasters thereby enhancing political capital. Thus, having access to resources and decision-making is the epitome of political capital. Community members with higher human capital and social capital will likely have higher political capital. For example, social organizations, such as faith-based groups, local advocacy groups, and schools connect with underserved community members, including the most socially vulnerable community members like homeless persons, and can help to establish some level of political capital for all.

Financial Capital

Financial capital describes the sum of financial assets and physical property that make up household wealth such as money in savings accounts, life insurance, pensions, housing, consumer durables, business investments. Access to credit and debt is also an element in the measurement of financial assets, and the size of the debt burden will have an impact on the level of household vulnerability. Each represent different types of wealth and differing levels of accessibility in times of need.

Severe financial consequences come with many risks, including the loss of income from job loss, or large, unexpected expenses from property damage or treating long-term illness. Community members or organizations with the highest net worth are best able to continue to meet their consumption needs when confronting adverse shocks. While the poor are less likely to have direct financial assets, they need access to insurance or credit to protect against shocks from disasters. The asset-poor and the income-poor are not necessarily the same groups (Morrone et al. 2011). For example, those with higher financial capital can use it to raise their human capital through education and consequently, social, cultural and political capital. On the other hand, asset-poor households can rely on friends and family for financial support and may not be as vulnerable as those without anyone to count on (provided such connections exist). Thus having good social ties and networks also alters how much financial capital is available in an emergency (Aldrich and Meyer 2014; Sutley et al. 2019).

Any organization offering employment therefore enhances financial capital in the community. Similarly, organizations themselves are investments as they produce goods or offer services fulfilling needs of the community. Banks and other investment-based organizations enhance financial capital, including homeownership. Homeownership is often the most significant financial asset in a household's financial portfolio. Therefore, damage to one's home can cause significant financial disruption.

Household incomes, longitudinal property values, and federal- and state- investments in a community can be used to measure financial capital (Peacock et al. 2014; Sutley and Hamideh 2017). The amount of available financial capital dictates the growth of built capital, which is particularly important when rebuilding after a disaster. The direct and indirect financial costs of a disaster involve addressing the distribution of financial resources, ensuring that interventions are cost-effective, cost of repaired or new post-disaster infrastructure, and increasing the diversity of economic resources. A community's post-disaster economy is essential not just for recovery, but also for mitigating future disaster risks. Proactive investments to rebuild the economy, therefore, is of utmost importance (Patel et al. 2017).

Cultural Capital

Cultural capital refers to language, symbols, mannerisms, attitudes, competencies, and orientations of local community members and groups (Ritchie and Gill 2011). Cultural capital differs from one community to the next and across a community depending on the people, and reflects the heritage of the people accordingly. Cultural capital reflects how a community perceives the world, their values, and their assumptions about how things fit together. This happens for individual community members at home, in school, and often through regular engagement with faith-based organizations. Culture creates the population's attitude and perception of life events, and sets the social rules related to power and influence in a community (Flora et al. 2004). Organizations, including government-based organizations, can facilitate cultural change, for example, through work environments or intentional programming.

Bourdieu (1986) points out that cultural capital exists in a system of exchange with financial and social capital. For example, with financial capital, access to prestigious educational institutions can be bought where valuable human capital and social capital are fostered. Eventually, it leads to acquiring elite forms of cultural capital. In turn, both the social and cultural capital accrued at an elite educational institute can be exchanged for economic capital via social connections, knowledge, skills, values, and behaviors that help one attain high-paying jobs (Cole 2019). On this ground, Bourdieu (1986) observed that cultural capital is often used to facilitate and enforce social divisions, hierarchies, and ultimately, inequality. Cultural growth is often used to reinforce class differences, historically and in the present day; different groups of people have access to different sources and forms of knowledge, depending on other variables like race, class, gender, sexuality, ethnicity, nationality, religion, and even age (Bourdieu 2018). As such, cultural capital can work for or against community resilience.

Aspects of culture necessary to community resilience include community members' belief in their ability to protect the well-being of the community, survive and thrive through change, and develop the necessary capacity to become resilient. These beliefs can be influenced by the trust individuals have in their community leaders and social networks, and thus communities with high social inequalities may not be able to leverage their cultural capital for resilience during and after disaster. Important risk, warning, and recovery information should be communicated in multiple languages to promote and foster cultural capital. After disaster, it is particularly important that recovery plans consider local culture, including in rebuilding efforts, such as was done in Texas after

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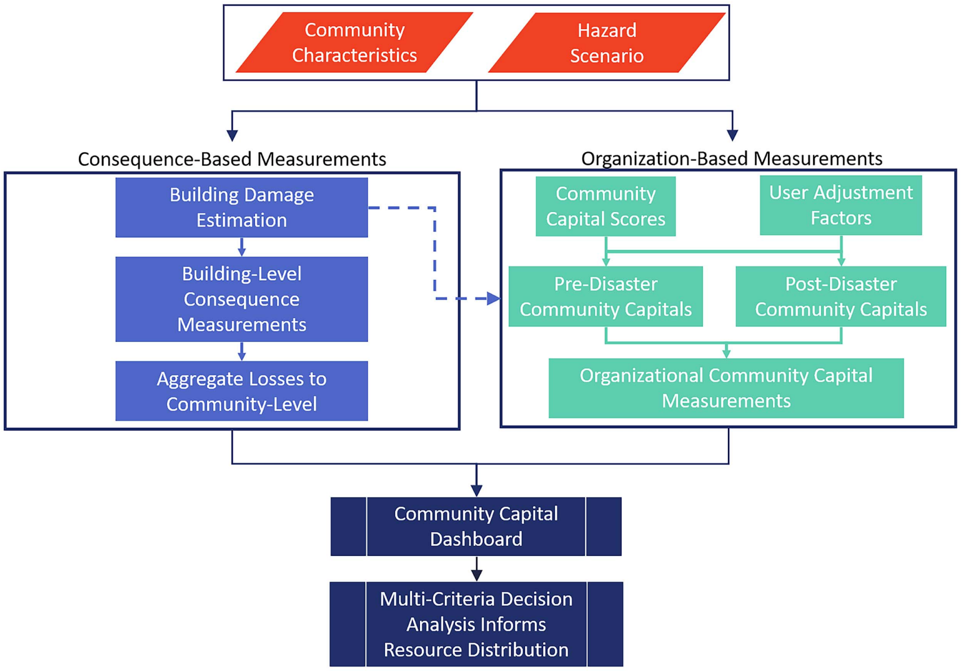

Fig. 1. Community capitals framework for linking buildings and organizations.

2008 Hurricanes Ike and Dolly with the RAPIDO temporary housing, which was managed in a manner that accounted for the local Latino culture (Van Zandt and Sloan 2017).

Natural Capital

Natural Capital is defined as resources such as air, land, water, minerals, oil, and the overall stability of ecosystems (Ritchie and Gill 2011). Conservation, development, and enrichment of natural capital is essential as the first and foremost need of human beings is to survive in an environment that sustains life. Natural capital is influenced by individual and collective human activities but also presents opportunities and limitations on human, social, cultural, and financial capitals (Machlis and Force 1997).

Natural capital intersects with environmental justice, and includes community members' exposure to environmental hazards and access to and use of environmental amenities, including tree canopy cover and greenspace (Low et al. 2005; Wolch et al. 2005; Schwarz et al. 2015). Important growth in human capital through improvement in mental and physical health (Saxon 2020), social capital through creating new linking relationships through coordinated activities, and cultural capital through specific events and practices that are a part of different cultures, are provided in shared spaces like parks. Equitable access to and use of nature's goods and equitable protection from its hazards, is a critical piece of natural capital in a community. As more and more people move to coastlines, so too, are they displaced and disrupted from disaster. It is critical that natural systems are taken into account in resilience planning and building design, including through floodplain management, so that a community's natural capital can be preserved and enhance quality of life, rather than manipulated in a way that works against resilience (Freudenburg et al. 2009; Tierney 2014).

A Community Capital Framework

A novel framework is proposed here that quantifies the multiple dimensions of a community using the community capitals to assess resilience. The framework is shown in Fig. 1, categorized by inputs, a two-pronged measurement system, and outputs.

To use the framework in Fig. 1, first, community characteristics, including the building portfolio and population data (e.g., total population count, number of households, number of users per occupancy type), and a hazard scenario (e.g., hazard type, intensity, hazard path or epicenter) are defined and input to the model. The inputs feed into a two-pronged approach to measure community capitals through (1) building-damage consequences; and (2) organization-based measurements, which are then aggregated to the community-level for a holistic view of disaster impacts and resource needs. The consequence-based measurement adopts metrics from the literature to quantify losses at a building-level. These metrics are then related back to community capitals, including dislocation (social capital, SC), morbidity (human capital, HC), accessibility (political capital, PC), and building repair costs (financial capital, FC). The consequence-based metrics are aggregated for all buildings across the community, and reported at the community-level. The organization-based measurement relates building occupancy type to each community capital considering the nature of the organization, including the goods and services it offers and how it interacts with its users. The number of buildings in each occupancy type are then used to quantify the influence building damage has on each community capital. Most organizations, or occupancy types, produce multiple types of community capital, and this indicates the significance of these buildings to the community. Both prongs adopt the same nomenclature used herein. The organizational loss variables start with an O, e.g., organizational built capital is OBC. The building damage consequences do not have any additional symbology, e.g., building-level built capital is denoted as BC. Each prong requires pre- and post-disaster measurement. Pre-disaster calculations are denoted with the subscript 0, e.g., pre-disaster built capital is BC_0. Post-disaster calculations are denoted with the subscript t, e.g., post-disaster built capital is BC_t. The formulations that follow are developed generally (e.g., without 0 or t subscripts). A case study is used to illustrate the framework, and provides pre- and post-disaster calculations as necessary.

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The results from the two-pronged approach are collectively reported to provide a broader understanding of community impact for the given hazard scenario. As output, a community capital dashboard is proposed for presenting trade-offs to decision-makers to further their understanding of how changes to community characteristics can affect community resilience. A dashboard enables the decision maker to see the trade-offs across multiple factors that influence community resilience, as opposed to a single (composite) measure or resilience index that may be too vague for a decision maker to understand. The results can be used to prioritize limited resources for retrofitting or rebuilding through an action plan that aligns with community priorities.

Relating Consequences of Building Damage to Community Capitals

The left-hand prong of the framework in Fig. 1 operates at the individual building-level. It builds off of the loss estimation literature, which has primarily focused on deaths, dollars, and downtime. For each building-level consequence, the loss is computed as the percent difference in the post-disaster value (e.g., BC_t) from the pre-disaster value (e.g., BC_0), expressed as

$$BCL = \frac{BC_t - BC_0}{BC_0} \cdot 100\% \tag{1}$$

where BCL is the built capital loss measured through the left prong in the framework in Fig. 1. Many approaches for estimating these losses can be found in the literature; the methods selected in this study are dependent on building damage. The following sections provide the computations for each of the measurements chosen for this research. Cultural capital is omitted due to a lack of research supporting a building damage-based metric.

A Metric for Built Capital

Looking back at Fig. 1, once a hazard scenario is defined and simulated, and the community characteristics, including population counts and building portfolio information, are known, then building damage is estimated for the community and classified into damage states. Damage states (DS) are distinct and sequential categories of damage to structural and non-structural components of a building associated with significant differences in expected casualties, usability, and repair costs and processes. Building damage states are numbered and labeled as 0 = None, 1= Slight, 2 = Moderate, 3 = Extensive, and 4 = Complete, where structural damage occurs at DS3 that requires occupants to dislocate until repairs can be completed (Sutley et al. 2017). Here, built capital, BC, is the number of functional buildings in the community measured as the number of buildings with no, slight, or moderate damage ($N_{DS0,i} + N_{DS1,i} + N_{DS2,i}$) across all occupancy types i, expressed as

$$BC = \sum_{i=1}^{t} (N_{DS0,i} + N_{DS1,i} + N_{DS2,i}) \tag{2}$$

A Metric for Social Capital

Household dislocation is used to measure social capital loss, SCL. Household dislocation is a common consequence of disaster and can be caused by building damage, neighborhood impacts, concerns of safety and wellbeing, access to alternative shelters or homes, and factors resulting from socio-economic, political and environmental impact (Sapat and Esnard 2016; van de Lindt et al. 2020). When community members dislocate from the community, or even their neighborhoods, social networks are interrupted (Erikson 1978). Social capital, SC, is measured here as the total number of residential buildings presumed to be occupied considering building damage state, BC_{res}, multiplied by the corresponding number of units in each residential building, n_{res}, for all residential buildings m in the community expressed as

$$SC = \sum_{res=1}^{m} n_{res} \cdot (BC_{res}) \tag{3}$$

A Metric for Human Capital

Fatalities and posttraumatic stress disorder (PTSD) are used here as measures of the impacts of a disaster on the population and taken as a proxy for human capital loss, HCL. These morbidities are the result of physical damage to structures as well as social characteristics such as age, ethnicity, health, and wealth status (Sutley et al. 2017; Norris et al. 2002). Extensive building damage and building collapses result in the majority of deaths (Shoaf et al. 1998), whereas building damage and damage to personal property have been linked to higher rates of PTSD in affected populations (Sharan et al. 1996; Ramirez et al. 2005). If the infrastructure is older and/or of poor quality the vulnerability of the associated population is much worse (Cutter et al. 2003).

Morbidity counts of fatalities and PTSD diagnoses are estimated here based on building damage. The mean value for each morbidity rate, $R_{M,DS}$, is provided in Table 2 (Sutley et al. 2017), where subscript $M = 1$ is Fatality, and $M = 2$ is PTSD here; additional morbidity types can be incorporated if rates and relationships to building damage are known. Morbidity counts, MB, was determined by summing the product of morbidity rate from Table 2; the presumed number of occupants, n_i^{occ}, per occupancy type from Table 3; and the number of buildings in each damage state, $N_{DS,i}$. This is expressed as

$$MB = \sum_{M=1}^{2} \sum_{DS=1}^{4} \sum_{i=1}^{m} (R_{M,DS} \cdot n_i^{occ} \cdot N_{DS,i}) \tag{4}$$

Human capital, HC, is determined as the pre-disaster population count, P_0, minus the morbidity count, MB, expressed as

Table 2. Mean morbidity rate, $\boldsymbol{R_{M,DS}}$, by damage state

Damage state	Fatality rate, $R_{Fatality,DS}$	PTSD diagnosis rate, $R_{PTSD,DS}$
1	0.0000005	0.000005
2	0.0000003	0.0003
3	0.00001	0.001
4	0.05	0.2

Table 3. Default occupancy counts

Occupancy type, i	Number of users per building, n_i^{occ}
Residential	Number of units times average household size (2.54 occupants per unit)[a]
Office, general	1 occupant/23 m^2 (per 250 sq ft)[b]
Retail	1 occupant/51 m^2 (per 550 sq ft)[b]
Industrial	1 occupant/232 m^2 (per 2,500 sq ft)[b]
Education, K-12	1 occupant/121 m^2 (per 1,300 sq ft)[b]

[a]US Census Bureau (2019).
[b]USGBC (2019).

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$$HC = P_0 - MB \tag{5}$$

Table 3 presents the details and references used for estimating number of users per building, n_i^{occ}, for a selection of occupancy types. For residential buildings, the number of users per unit was taken as the US average household size (2.54 persons) based on the US Census Bureau (2019). For general office buildings, retail, industrial, and education buildings, the occupancy estimate was based on a number of occupants per building footprint from USGBC (2019).

A Metric for Political Capital

Political capital helps in understanding social inequities and the political ecology of a community through roles of capital formation at different geographic scales in promoting community member's access to different forms of capital, both directly and through engaging with state, market, and other civil society actors (Bebbington and Perreault 1999). Political capital includes access to many types of resources. Here, political capital, PC, is measured as the number of essential community services, ECS, such as schools, hospitals, and fire stations, located within a specified distance, d, of one's home, expressed as

$$PC = \sum_{s=1}^{l} ECS_s^d \tag{6}$$

where s is the the type of essential community service, and l is the total number of ECS being considered. Neighborhood boundaries may be defined such that building-level estimates of political capital can be averaged at the neighborhood level. If used, neighborhood boundaries should be defined as no larger than a census block, but should be somewhat self-evident. The post-disaster measure accounts for whether any of the ECS were damaged to the point of being unavailable/not functional.

A Metric for Natural Capital

Community members' access to and use of environmental amenities, including greenspace, parks, mountains, beaches, and the like, represent a community's natural capital (Low et al. 2005; Wolch et al. 2005; Schwarz et al. 2015). Here, natural capital, NC, is measured as the number of green spaces, GS, such as parks, mountains, beaches, located within a specified distance, d, of one's home, expressed as

$$NC = \sum_{g=1}^{h} GS_h^d \tag{7}$$

where g is the type of green spaces, and h is the total number of GS being considered. Similar to political capital, neighborhood boundaries may be defined such that building-level estimates of natural capital can be averaged at the neighborhood level. The post-disaster measure accounts for whether any of the GS were damaged to the point of being unavailable/not useable.

A Metric for Financial Capital

The financial impact of a disaster can be estimated through direct and indirect losses, which include infrastructure repair, business disruption, household dislocation costs, among others. To simplify the framework, here, only direct losses are included. The total building value is comprised of cost estimates of drift-sensitive structural components γ^{SD}, drift-sensitive non-structural components γ^{ND}, acceleration-sensitive non-structural components γ^{NA}, and building contents γ^{CV}. A damage ratio p_{ds}, which is the proportion of component and content value damaged given the damage state, is multipled by the component and content cost. Financial capital may also include any investment cost for building retrofitting or hardening HC. Considering all of these, the financial capital, FC, is estimated as

$$FC = \sum_{i=1}^{m} \left[\sum_{DS=1}^{4} (\gamma_{DS,i}^{SD} p_{DS,i}^{SD} + \gamma_{DS,i}^{ND} p_{DS,i}^{ND} + \gamma_{DS,i}^{NA} p_{DS,i}^{NA} + \gamma_{DS,i}^{CV} p_{DS,i}^{CV}) + HC_i \right] \tag{8}$$

Relating Organizations to Community Capitals

The right side of Fig. 1 presents the approach to the organization-based measurements formulated in this section. First, a community capital score, s_{ij}, and adjustment factor, a_i, are computed using community characteristics, including building portfolio and population information, for each occupancy type i and community capital j. Second, relationships between the community capitals and building occupancies are assigned, and employed before and after the hazard scenario. Organizational community capital, OCC_j, is computed as

$$OCC_j = \sum_{i=1}^{m} a_i \cdot s_{ij} \cdot N_i \tag{9}$$

where j is a specific community capital, i.e., built, social, human, cultural, political, financial, or natural; i is a specific occupancy type; m is the total number of occupancy types being considered; a_i is the adjustment factor for occupancy type i and s_{ij} is the community capital score for occupancy type i and community capital j, which are defined in the next sections; and N is the total number of functional buildings of each occupancy type across the community. Organizational community capital loss, $OCCL$, is measured as the difference in the number of functional buildings before and after the disaster ($N_t - N_0$), multiplied by the adjustment factor a_i and community capital score s_{ij}, expressed as

$$OCCL_j = \sum_{i=1}^{m} a_i \cdot s_{ij} \cdot (N_{0,i} - N_{t,i}) \tag{10}$$

The units of OCC and $OCCL$ are effectively the number of households impacted by the community capital j being measured.

Community Capital Score

The community capital score, s_{ij}, is developed for each community capital and selection of occupancy types using the community capital definitions in Table 1. Occupancy type is used here to classify buildings based on how they are used by building occupants and the community, and is more specific than the occupancy descriptions in ASCE 7 (ASCE 2017). For example, residential buildings are split into two categories, single family dwelling (SFD) and multi-family dwellings (MFD). This distinction is made in an attempt to control for the number of users of the building, and is explained in more detail in the next section. Table 4 provides the criteria, extracted from the definitions presented in Table 1, and associated criterion weights (w_j) for each community capital. Values of w_j, which range from 0.2 to 1.0, are calculated as the inverse of the total number of criteria for each capital. For example, built capital has a criterion weight of 1.0 since only buildings are being analyzed here, and thus all structures exactly match the single criterion listed in the built capital definition. There are three criteria in the definition of social capital, namely, networks, associations, and trust generated, and thus w_j is 0.33. In re-use of the framework,

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Table 4. Community capital criteria weight

Type of capital	Criteria	Criterion weight, w_j
Built	Buildings	1.00
Social	Networks, associations, trust generated	0.33
Human	Knowledge, skills, health, physical ability	0.25
Cultural	Language, mannerisms, attitudes, competencies, orientations	0.20
Political	Access to resources, ability to influence resource distribution, ability to engage external entities in efforts to achieve goals	0.33
Financial	Savings, income, investment	0.33
Natural	Stability of resources such as air, water, land, minerals and oil	0.20

if additional criteria or scope is included in the analysis, the values in Table 4 will need to be updated accordingly.

Community capital score, s_{ij}, is computed as the product of the weight, w_j, and the number of criteria satisfied for each occupancy type, $crit_i$, expressed as

$$s_{ij} = w_j \cdot crit_i \tag{11}$$

Table 5 provides the community capital scores for a selection of occupancy types (selected from Fedders 2018 and Ellingwood et al. 2016) using the criteria and weights in Table 4 and calculated using Eq. (11). The rationale for the number of criteria satisfied for each occupancy type in Table 5 is detailed in Daniel (2019), and summarized here. Natural capital is left out of Table 5 given the lack of research enabling its quantification with respect to organizations occupying buildings.

For social capital, SFDs foster strong relationships and generate trust, but do not further develop networks given the limited scope of the occupants. SFDs satisfy two of the three social capital criteria in Table 4 and thus have $s_{SFD,SC} = 0.67$ in Table 5. MFDs, commercial buildings, faith-based organizations, educational organizations, and healthcare organizations can do all three: build networks, foster relationships, and generate trust. For human capital, specific organizations like hospitals and schools are designed to build knowledge, skills, health, and physical ability; other organizations, like recreational facilities primarily contribute to health and physical ability, whereas industrial facilities primarily contribute to knowledge and skills. For political capital, faith-based organizations stimulate local activity, and increase interactions. Similarly, schools provide a fundamental resource through education and guidance thereby enhancing political capital.

Table 5. Community capital score, s_{ij}

Occupancy type, i	Built capital	Social capital	Human capital	Cultural capital	Political capital	Financial capital
SFD	1.00	0.67	0.25	1.00	0.00	1.00
MFD	1.00	1.00	0.25	1.00	0.00	0.67
Retail	1.00	0.67	1.00	0.60	1.00	1.00
Government	1.00	0.67	1.00	0.60	1.00	1.00
Commercial	1.00	1.00	1.00	0.80	0.67	1.00
Entertainment	1.00	0.33	0.25	0.00	1.00	1.00
Storage	1.00	0.00	0.00	0.00	0.00	0.33
Faith-based	1.00	1.00	0.00	1.00	1.00	0.33
Civic	1.00	0.67	0.50	0.20	0.33	0.33
Recreational	1.00	0.67	0.50	0.00	0.33	0.33
Industrial	1.00	0.67	0.50	0.00	0.33	1.00
Education	1.00	1.00	1.00	1.00	1.00	0.67
Healthcare	1.00	1.00	1.00	0.00	1.00	1.00
Emergency	1.00	0.67	1.00	0.00	1.00	0.67
Utility	1.00	0.00	0.00	0.00	0.00	1.00

Adjustment Factors

Adjustment factors, a_i, are necessary to account for the number of users of a building to (1) capture and amplify the importance of highly trafficked buildings like hospitals, and (2) reduce the influence of common building types that individually impact few households (e.g., SFD). Adjustment factors are calculated as

$$a_i = \frac{n_i^{occ}}{Average\ household\ size} \tag{12}$$

This adjustment factor is effectively the number of households immediately impacted by loss of the facility. The values in Table 3 are used for estimating number of users per building, n_i^{occ}, for a selection of occupancy types in Eq. (12).

Exemplifying the Framework on the Centerville Virtual Testbed

Centerville is one of the testbeds developed as part of a National Institute of Standards and Technology (NIST) funded Center of Excellence for Risk-based Community Resilience Planning (Ellingwood et al. 2016). Fig. 2 portrays the map of Centerville, a virtual city of moderate size located in a Midwestern state with approximately 50,000 in population. The city is roughly rectangular with an 8 km by 13 km (5 mi. by 8 mi.) plan. There is a railway line that follows the east side of the Rock River that runs through the center of the city.

Centerville's building portfolio consists of 16 building archetypes that include residential, commercial, and industrial occupancies, as well as critical facilities including hospitals, fire stations, schools, and government offices. There are seven residential neighborhoods in Centerville, with a mix of high income/low density (HI/LD) and middle income (MI) or low income (LI) residential areas, and a mobile home park. Sutley and Hamideh (2020) identified Residential Zone 1 (Z1) as the least socially vulnerable, and Zone 7 (Z7) as the most socially vulnerable neighborhood in Centerville. There are two commercial/retail zones in the southern part of the city. Local government facilities are in the center of town, near the river. There are two relatively large industrial facilities. One regional hospital serves Centerville and the surrounding county. The public school system includes four elementary, three middle, and one high school. Details of the building portfolio are provided in Table 6, where the number of buildings and floor area for each occupancy type are originally obtained from Lin and Wang et al. (2016), subsets of occupancy types correspond to HAZUS-MH fragility functions (FEMA 2003), and the number of building occupants, at peak occupancy, is based off of the estimates in Table 3.

A seismic hazard analysis was performed on Centerville in Lin and Wang (2016), and is adopted here. The hypothetical scenario earthquake is a Mw 7.8 with an epicenter located approximately 40 km southwest of Centerville. Building characteristics such as occupancy, structural type, construction material, number of stories, plan area, and year built are used to map seismic damage fragility functions using the HAZUS-MH database (FEMA 2003) corresponding to the nomenclature in the first column of Table 6 (e.g., W1 is wood building type 1; S is for steel braced frame buildings; RC is reinforced concrete frame buildings; and RM is

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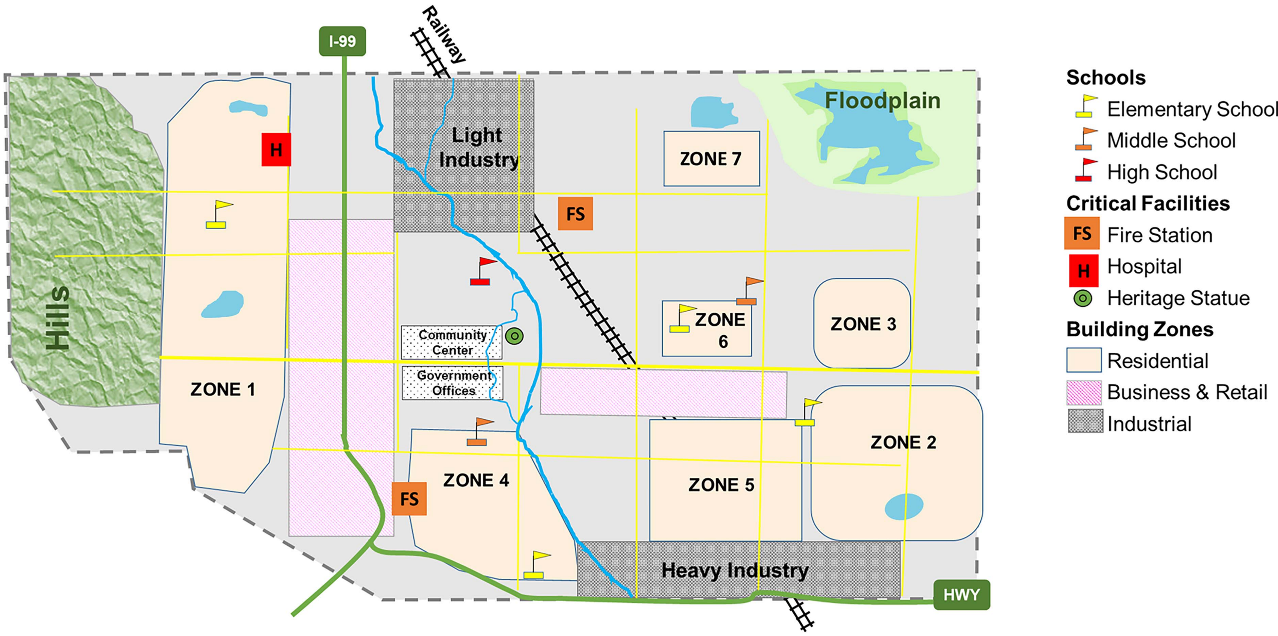

Fig. 2. Map of Centerville. (Adapted from Ellingwood et al. 2016.)

reinforced masonry buildings). Occupancy rate modifications are made to account for the earthquake occurring during typical work day hours, such that not all buildings in Centerville are completely occupied at the time of the earthquake. Occupancy rate modification factors used here are 0.2 for residential buildings, 0.6 for retail buildings, and 1.0 for all other occupancies.

Building-Level Loss Measurements

The earthquake scenario considered utilizes the ground motion attenuation model by Campbell (2003) and the capacity spectral method to determine the intensity measure for building components considering the building zones labeled in Fig. 2 (Lin and Wang 2016). Damage state probabilities are estimated accordingly, and used to portion damage state assignments across occupancy type and zone. The earthquake scenario resulted in 10% of buildings experiencing either severe or complete damage (DS3 or DS4) rendering them not functional. Table 7 provides the pre-disaster built capital BC_0, post-disaster built capital BC_t, and the built capital loss BCL for each occupancy type i. As shown in Table 7, the highest built capital loss was to retail facilities (39%), followed by government buildings (38%), industrial buildings (16%), and then residential buildings (10% for SFD and 8% for MFD), where the occupancy type with the largest number of buildings rendered unfunctional were single family dwellings. As a result of this damage, approximately 10% of households are dislocated; social capital values are shown in Table 8 for SFD, MFD, and in total, where each MFD has 48 units. The geographical depiction of building damage states is shown in Fig. 3(a), and for household dislocation in Fig. 3(b) for Centerville. Higher concentrations of damage and dislocation are evident in Zone 7, the mobile home park, and zone 4, which is characterized as median income and high density.

Eq. (4) and Table 2 are used to evaluate the morbidity caused by the building damage estimates. Overall, human capital loss

Table 6. Centerville building stock

Occupancy type	Number of buildings in Centerville	Floor area [m^2 (sq ft)]	Number of building occupants
Single-family residential	14,788	—	—
W1	6,190	130 (1,400)	2.54
W2	4,000	223 (2,400)	2.54
W3	50	297 (3,200)	2.54
W4	3,196	223 (2,400)	2.54
W6	1,352	—	2.54
Multi-family residential, W5	102	3,345 (36,000)	122
Retail	159	—	—
S1	45	4,645 (50,000)	91
RC1	24	4,645 (50,000)	91
RM1	76	2,322 (25,000)	45
S2	6	11,613 (125,000)	227
Industrial	70	—	—
S3	25	9,290 (100,000)	50
S4	45	46,451 (500,000)	200
School	8	—	—
RC3	4	9,290 (100,000)	77
RM3	4	9,290 (100,000)	77
Hospital, RC2	1	11,148 (120,000)	480
Fire station, RM2	2	929 (10,000)	40
Government, RC1	8	4,645 (50,000)	200
Total	15,130	—	—

Table 7. Built Capital Loss, BCL, measured through functional building inventory

Occupancy type, i	$BC_{0,i}$	$BC_{t,i}$	BCL_i (%)
SFD	14,788	13,282	10
MFD	102	94	8
Retail	151	93	39
Industrial	70	59	16
School	8	8	0
Fire station	2	2	0
Hospital	1	1	0
Government	8	5	38
Total	15,130	13,543	10

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Table 8. Social Capital Loss, SCL, measured through household dislocation

Residential occupancy type, res	$SC_{0,i}$	$SC_{t,i}$	SCL_i (%)
SFD	14,788	13,282	10
MFD	4,896	4,492	8
Total	19,684	17,774	10

included 61 fatalities and 250 persons with post-traumatic stress disorder. Taking the initial population count as 50,000 people, HCL is estimated as 0.6%. Due to the fact that retail buildings have high occupancy counts and experienced the highest BCL, they also caused the highest proportion of HCL, including 178 morbidities. None of the essential service buildings, including the hospital, fire stations, and school buildings, were rendered non-functional from the earthquake. As such, there is no building-level political capital loss, PCL, in this example. The earthquake did not cause any damage either to the green spaces in Centerville, including the mountains on the west side and lake on the northeast side of town, or to the built environment that disrupt or reduce access to the green spaces; as such no building-level natural capital, NCL, is lost in this example.

As described earlier, damage ratios are used to evaluate direct losses (repair cost and content loss) of each occupancy type. Repair costs for each occupancy type are presented in Table 9; the total

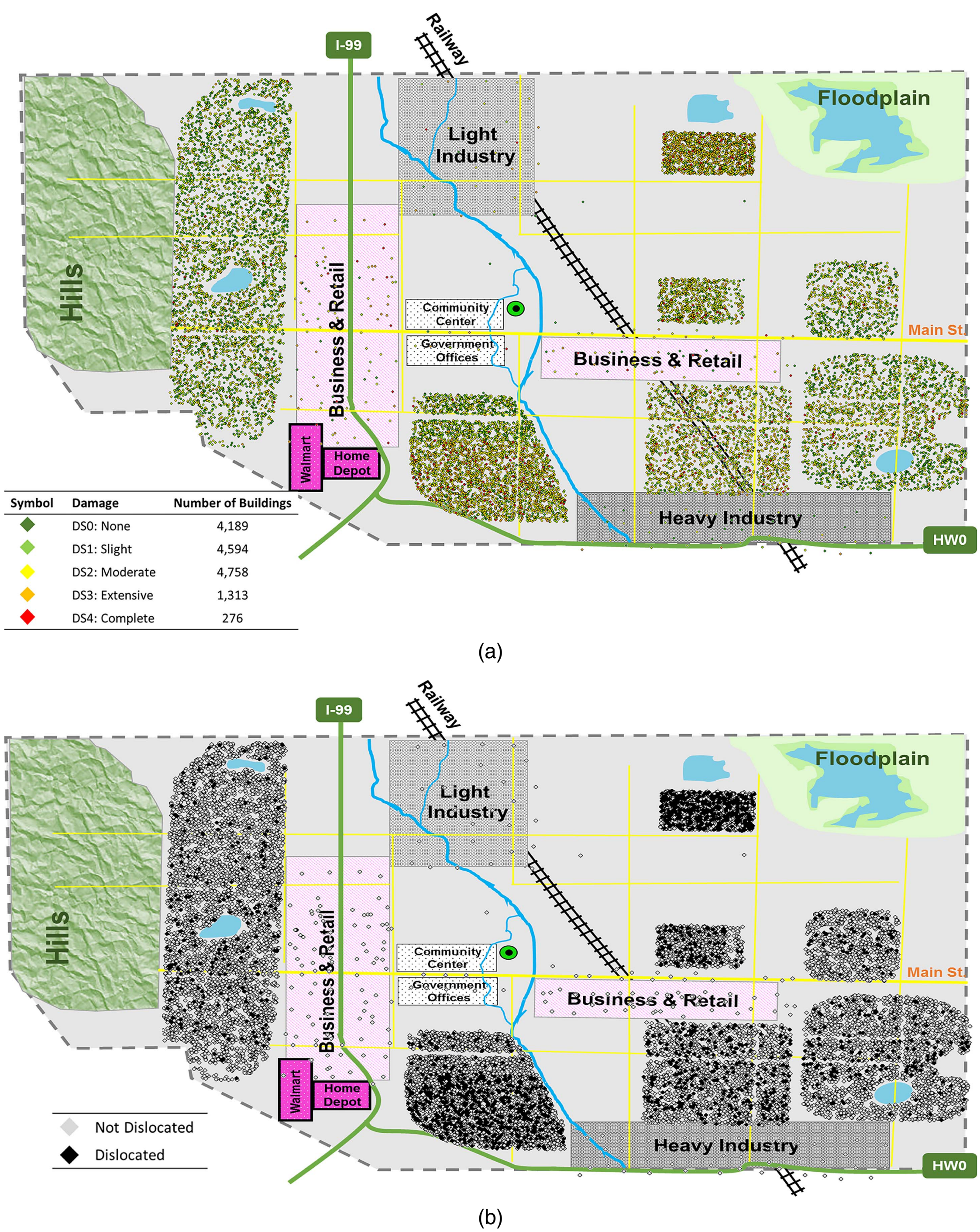

Fig. 3. Post-earthquake (a) building damage states; and (b) household dislocation in Centerville.

Table 9. Financial Capital Loss, FCL, measured through direct losses

Occupancy type, i	$FC_{0,i}$ (billion USD)	$FC_{t,i}$ (billion USD)	FCL_i (%)
SFD	4.023	3.669	9
MFD	0.600	0.541	10
Retail	1.127	0.983	13
Industrial	4.883	4.605	6
Education	0.148	0.140	5
Fire station	0.005	0.005	10
Hospital	0.043	0.040	6
Government	0.079	0.068	14
Total	10.91	10.05	8

financial capital loss is estimated as 8% or $856 Million (USD). Damage to single family dwellings ($354 Million USD) followed by industrial buildings ($277 Million USD) resulted in the most financial capital loss of all occupancy types considered.

Community-Level Loss Measurements

Adjustment factors computed for Centerville using Eq. (12) are provided in Table 10. For the case of Centerville, the adjustment factor for hospitals is 189 whereas for SFD it is 1. As stated previously, the adjustment factor is effectively the number of households immediately impacted by loss of the facility. As estimated here, loss of a hospital impacts approximately 189 times as many households as the loss of one SFD causes for the case of Centerville where there is only one hospital and nearly 15,000 residential buildings.

Table 11 provides the sum across all occupancy types to estimate the total pre-and post-disaster organizational community capital, OCC_0 and OCC_t, respectively, as well as reporting the organizational community capital loss, $OCCL$. Recall, the units for OCC and OCCL are essentially the number of households dependent on the organization. As expected based on the framework

Table 10. Adjustment factors

Occupancy type	Adjustment factor
SFD	1
MFD	48
Retail, S1 and RC1	36
Retail, RM1	18
Retail, S2	89
Industrial, S3	16
Industrial, S4	79
School	30
Hospital	189
Fire station	16
Government	79

Table 11. Organizational community capital loss

Community capital, j	OCC_{0j}	OCC_{tj}	$OCCL_j$	Percent difference (%)
Built	29,118	21,741	7,377	25
Social	21,266	16,165	5,101	24
Human	12,377	8,285	4,093	33
Cultural	22,934	19,868	3,067	13
Political	6,784	3,798	2,986	44
Financial	27,412	20,194	7,219	26

Table 12. Proportion of organizational community capital loss by occupancy type

Occupancy type, i	Built (%)	Social (%)	Human (%)	Cultural (%)	Political (%)	Financial (%)
SFD	2	20	9	49	0	21
MFD	7	9	3	16	0	4
Retail	21	21	38	31	52	22
Industrial	49	47	44	0	40	50
School	0	0	0	0	0	0
Hospital	0	0	0	0	0	0
Fire station	0	0	0	0	0	0
Government	3	3	6	5	8	3
Total	100	100	100	100	100	100

formulations, organizational built capital loss impacts the most households; it drives the other capitals. However, $OBCL$ does not create the largest percent difference. OPC experienced the greatest percent loss (44%) due to the government buildings that were damaged during the earthquake, followed by OHC (33%). Table 12 presents the $OCCL$ for all capitals by occupancy type.

As shown in Table 12, the scoring system presented in Tables 4 and 5 did not create unique values for all capitals and occupancy types. The zeroes in Table 12 are similarly reflective of the scoring system. As evident in Table 12, industrial buildings produced the most OBC, OSC, OHC, and OFC, implying that damage to industrial buildings will negatively impact many households in Centerville, and will significantly degrade Centerville's resilience.

Community Capital Dashboard and Decision Analysis

The losses caused by the earthquake scenario in Centerville are presented as a dashboard in Fig. 4. The bar charts on the left side, presented as Figs. 4(a–c), report the organizational community capital loss, pre-disaster measure and post-disaster measure, respectively, where the loss is presented as occupancy proportions of the total loss for each capital. The natural capital is not shown in the dashboard since there is no loss in natural capital due to the scenario earthquake. From Fig. 4(a), industrial and single-family dwellings account for the majority of loss caused by the earthquake. On the right side of Fig. 4, the building-level consequences are reported for the built, social, human, financial, and political capitals, respectively. As shown, the earthquake scenario rendered 10% of buildings non-functional, displaced 10% of Centerville households, caused 61 fatalities, 250 cases of PTSD, $856 Million (USD) in direct losses, but did not disrupt or reduce access to any essential community services or green spaces.

A dashboard was selected for presenting the community capital measurements to provide a holistic view of disaster losses to inform risk-based decision-making. For example, if a user prioritized financial capital as the most important, then they would prioritize resources to enhance the performance of single family dwellings and industrial buildings which caused the most FCL ($354 Million USD) and OFCL (3,590), respectively. Recall, FCL is repair costs and content loss, and OFCL is the number of households impacted by institutions contributing to financial capital through savings, income, and investment. If a user prioritized human capital as the most important, then they would prioritize resources to enhance the performance of retail buildings, which resulted in 178 morbidities, and industrial buildings, which impacted 1,115 households (OHCL) as measured through industrial buildings' contribution to knowledge, skills, health, and physical ability. If financial and cultural capitals are equally prioritized as most important, then accordingly, resources would be designated to improve the seismic

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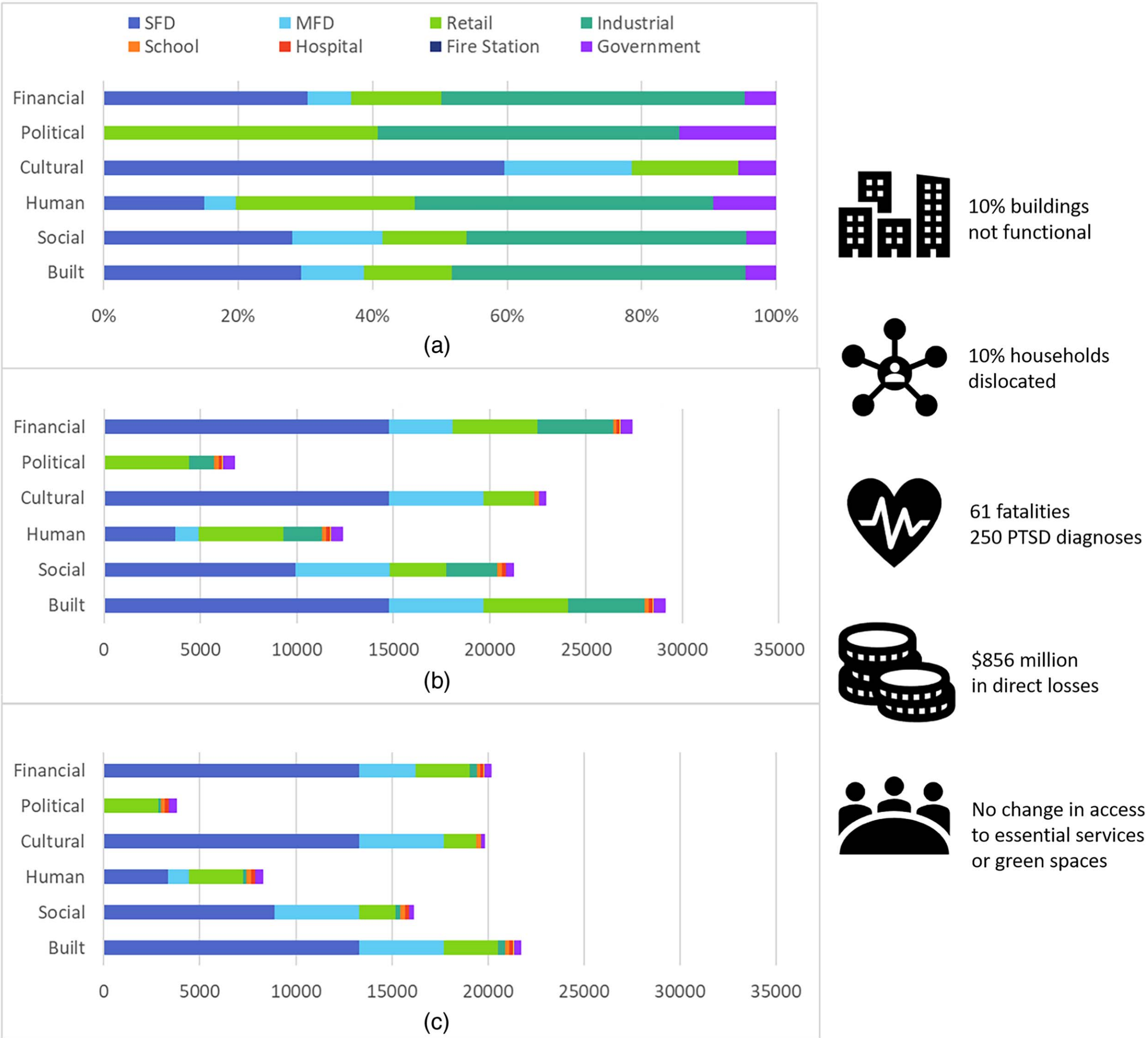

Fig. 4. Community capital dashboard for Centerville following a moderate earthquake scenario: (a) organizational community capital loss; (b) pre-disaster organizational community capital; and (c) post-disaster organizational community capital.

performance of single-family homes. In all cases covered in the present example, investing in the protection of any one community capital will have positive impacts on protecting multiple (and sometimes all) other capitals.

Conclusions and Areas of Future Research

The two-pronged framework provides three major contributions to the community resilience literature by (1) providing a literature review on each of the community capitals and their intersection; (2) combining what is already established in the literature in terms of post-disaster human and building loss estimations; and (3) combining the community capitals quantitatively into a single, executable framework. The proposed framework is based on the assumption that different building occupancy types—through their organizations—generate different community capitals and thus provide a system to measure this generation. The illustrative example demonstrated how buildings are related to the community capitals, and how a user (community) might distribute resources differently based on the community capital(s) they prioritize most.

In the Centerville example, retail buildings led to the most morbidities (human capital loss), whereas single family dwellings (through consequence-based measurements) and industrial buildings (through organization-based mesuarements) led to the most built, social, financial, political, and cultural capital losses. Distributing resources to prevent loss in any individual capital will have positive ripple effects on other capitals, decreasing losses throughout.

The measurements presented here, while an important advancement in accounting for holistic integration of the technical, organizational, social, and economic systems imperative to a community's functionality, are proxies and require further research. Future work may advance the presented framework through:

- Quantifying the difference in bonding, bridging, and linking social capital generated by different organizations;
- Advancing knowledge on both natural and cultural capitals as they relate to buildings and organizations;
- Extending the framework to include other built capital, such as transportation, power, water, and other infrastructure systems; and
- Validating the selection of criteria, assigned scores, and adjustment factors, or otherwise refine their measurement.

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Data Availability Statement

All data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

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