diverse plant natural products may play essential roles in plant resistance to pathogens (*8*).

Fu *et al*. find that another QTL, *Yr36*, which provides quantitative resistance to stripe rust, harbors the gene *WHEAT KINASE START 1* (*WKS1*). The WKS1 protein contains a steroidogenic acute regulatory protein–related lipid transfer domain (START) and a functional enzymatic (kinase) domain, suggesting a role for plant lipids in cell signaling mechanisms that confer disease resistance. This specific combination of domains, unique among plants examined to date, appears to have evolved just before the divergence of wheat and its closest relatives. However, although *WKS1* provides resistance to diverse stripe rusts, the resistant allele is present in only a minority of the species tested, and even within the species in which *WKS1* occurs, it is not ubiquitous across all genotypes. This suggests that the gene evolved early in the wheat lineage and was then repeatedly lost. Natural variation of gene function is also a hallmark of gene-for-gene resistance loci, where continual shifts in pathogen populations are believed to drive rapid evolution of these genes (*9*, *10*). Given the dearth of cloned quantitative resistance loci, it remains to be seen if these loci show enhanced levels of polymorphism and evolutionary dynamics similar to those for gene-for-gene resistance.

Why don't pathogens evolve counter-resistance to durable plant resistance? Perhaps these quantitative resistance loci target components of pathogens that are so critical for pathogen success that their encoding genes are evolutionarily constrained relative to similar pathogen genes involved in gene-for-gene interactions. Alternatively, these quantitative genes may provide resistance to the plant at less detriment to pathogen fitness than do gene-for-gene resistances. In both scenarios, decreasing the selective pressure for pathogens to evolve counter-resistance promises greater long-term success for improving crop yields using durable quantitative plant defenses. Additionally, for both cloned QTL described by Krattinger *et al.* and Fu *et al.*, alleles associated with loss of plant resistance to the tested pathogens would be predicted to produce modified, rather than nonfunctional proteins. Future inquiry into possible alternative functions of these genes or fitness costs of possessing resistant alleles at these loci may provide further insight into the evolution and durability of these mechanisms.

The studies by Fu *et al*. and by Krattinger *et al*. provide a first glimpse into the molecular mechanisms controlling quantitative resistance. Together, they demonstrate that multiple mechanisms can contribute to quantitative resistance within a given plant and that these mechanisms are not obviously associated with the well-studied and taxonomically widespread specific gene-for-gene resistance mechanisms. Mechanisms of quantitative resistance may be unique to particular plant lineages. Thus, while providing valuable tools to develop durable resistance against important wheat pathogens, these studies also argue that the molecular mechanisms of quantitative resistance need to be studied in a wide range of crop and model plants to fully explain the phenomenon.

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10.1126/science.1171410

ENGINEERING

Infrastructure Design Issues in Disaster-Prone Regions

Advances in infrastructure assessment and design should help designers and builders support sustainability and resilience goals.

Seth D. Guikema

If designed and managed well, infrastructure—the networks that transport people and goods, distribute energy, and maintain communications and the buildings in which people live, work, and play—contributes to societal sustainability and resilience in areas at substantial risk from catastrophic events such as hurricanes. The extent to which infrastructure functions after such events depends on design choices that trade off, at least implicitly, current construction costs for future repair and replacement costs. These choices are based on assumptions that may not reflect all of the relevant factors.

Recent advances in assessment and design allow the economic and environmental trade-offs in both design and postdisaster restoration to be explicitly considered and managed proactively during the design process. Similarly, infrastructure design can take advantage of the interactions between the natural and built environments in disaster-prone regions.

For example, we have an extensive record of hurricane impacts and can design structures to withstand those impacts in many cases. Despite advances in our knowledge of structural design for hurricane-prone areas, economic damage to buildings from major hurricanes in the United States has remained largely steady over the past four decades when adjusted for population growth and inflation (*1*, *2*) (see the figure, panel A).

Consider as an example a new commercial development to be built in a hurricane-prone area. Traditional design practice would be to design the individual buildings, utility poles, water distribution pipes, and flood protection systems to meet the design wind speeds and flooding levels specified in the relevant standards (*3*) or occurring with a preselected yearly probability. Current standards (*3*) specify that most structures (except for critical structures such as emergency response facilities) should be designed to withstand the stresses imposed by a hurricane that would occur, on average, every 50 years. This approach makes three fundamental assumptions that should be questioned.

First, it implicitly assumes that the design standards strike the proper balance between the benefits and costs of different design alternatives. Design standards are intended to apply across many different buildings, each with location-specific costs of reinforcement and failure. For example, two neighboring low-rise industrial buildings may have been

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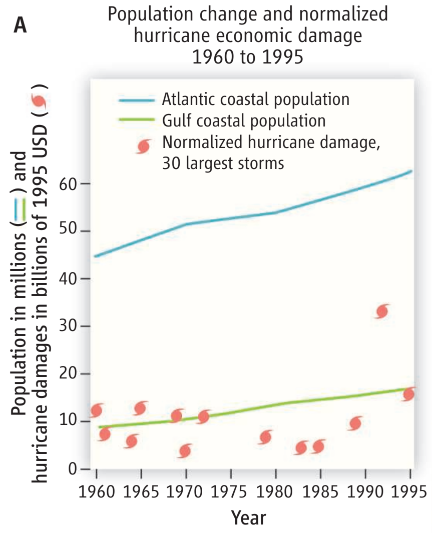

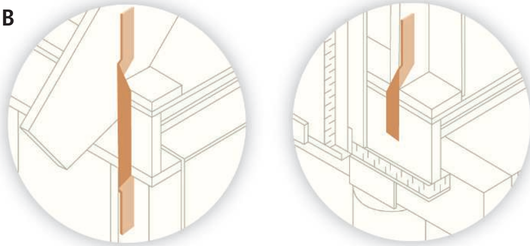

Hurricane strap ties transfer the load from the roof rafters down through the studs and into the foundation systems

Exposed to the elements. (**A**) Normalized insured economic losses from the 30 most damaging hurricanes in the United States and population growth (*1*). Economic losses are normalized for population growth, inflation, and property values using 1995 dollars, with each point representing the total economic loss in that year from the 30 major hurricanes. Years with no losses are not shown. Coastal population estimates are from the U.S. Census Bureau (*2*). (**B**) Use of hurricane straps in residential construction (*16*). (**C**) A hurricane-resistant dome home (*17*).

built at the same time and may be structurally similar. Yet, if one contains low-value manufacturing while the other houses high-value computer chip manufacturing involving hazardous chemicals, the costs of failure during a disaster will be dramatically different. Standardized design codes do not directly account for these differences.

Second, it assumes that the life-cycle environmental impacts of the development should not directly enter design decision-making, particularly the selection of the level of robustness of the system. However, contaminant releases, degradation of ecosystems, and impacts on communities surrounding the facility must also be considered. These burdens are real, even if hard to measure.

Third, it assumes that the design decision-making should not consider depending on or enhancing protection offered by natural ecosystems. For example, in designing a levee system to protect New Orleans, the flood-damping benefits of marshes and barrier islands were not explicitly considered as part of the design process. These natural buffer systems have been degrading over time, potentially decreasing the level of protection afforded by the engineered system (*4*). Both marsh restoration and designed facilities can be important parts of the protection system.

Recent advances have allowed engineers to consider a wider range of impacts in the design process. These include the life-cycle financial impacts of failures during disasters (*5*, *6*), enabling increased up-front reinforcement cost to be balanced against the uncertain costs of failures during disasters. Indirect economic costs of infrastructure failures, including loss of business revenue and economic growth in impacted areas, can also be included based on modified regional economic input-output models incorporating adaptation (*7*). These types of models suggest that indirect economic costs are at least twice as high as direct losses from major disasters. Environmental life-cycle inventory analysis allows the outcomes to be further broadened to include contaminant emissions and energy use over the life cycle of a built facility (*8*–*10*).

The interactions between natural ecosystems and built infrastructure are now better understood in many regions. In particular, mangrove swamps and other coastal vegetation can reduce the impacts of hurricane winds, hurricane surges, and tsunamis on infrastructure (*11*–*14*), with submerged marsh vegetation alone offering the potential of up to 30% reductions in wave heights (*14*). The damping effects of natural ecosystems can be taken advantage of by integrating ecosystem restoration in the infrastructure design process and then adapting the resistance of the components of the infrastructure systems to account for the modified loading, building from recent advances in understanding stresses imposed by hurricanes (*15*).

Initial steps have been taken toward the integrated design approach suggested here. For example, residential homes can be built with a modified, elevated foundation, materials that are stronger and more resistant to mold, hurricane straps (see the figure, panel B), and improved building envelope sealing, moisture management, and insulation. This approach can decrease energy costs by $600 to $1000 per year and yield a home substantially more resistant to costly failure during hurricanes while maintaining a traditional architectural appearance (*16*). With a less traditional design, "dome homes" (*17*) (see the figure, panel C) provide another highly hurricane-resistant approach that has seen successful, although limited, use. However, further work is needed to fully account for and take advantage of the interactions between the natural and built environments. The optimal design is one that considers the full impacts of infrastructure on the surrounding environment and community and the influence of the surrounding environment on the built facility.

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10.1126/science.1169057

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