DOI: 10.1111/nrm.12149

WILEY Natural Resource Modeling

Ecological resilience in the face of catastrophic damage: The case of Hurricane Maria in Puerto Rico

Puerto Rico is not only coastal beaches and San Juan nightclubs. More than half the population lives in smaller cities and towns and is, what the big city folks refer to as "la isla" (literally, the island, metaphorically, the countryside). As in all rural settings, agriculture looms large as an economic backbone and, for much of the island, the agriculture is based on coffee production. Yet coffee is not only an economic backbone, it is part of a general landscape that looks a lot like a natural forest. The traditional way of growing coffee is under the shade of a tree canopy (it is, after all, originally an understory shrub from eastern Africa), only recently "modernized" by deforesting its natural setting, which is to say, eliminating the shade under which it naturally prospers. It has been argued that the shade tree layer, so common in the older more traditional style of producing coffee, provides us—the coffee farmers, the coffee drinkers, the people of Puerto Rico—with what is usually referred to as "ecosystem services." With trees come the natural enemies that eat the potential coffee pests, the bees that help pollinate the coffee, the tree trunks that store carbon, the shade levels that help produce high-quality coffee, the habitat in which the endangered Puerto Rican parrot lives, and other "services." A significant controversy in this field—provisioning of ecosystem services—is whether the various services that attend to particular methods of production are antagonistic to one another, or whether they can be synergistic.

Elementary considerations suggest that either is possible. Taking two arbitrary services into account (say, yield of coffee and carbon storage), we can view the problem as a classical tradeoff problem, in which ecological factors and economic factors are codependent. So, for example, the set of all possible planting patterns (called the "service set"), has an outer boundary, one of the points of which will be "optimum." That optimality will be dependent on a "value function" which combines the values (an abstraction intended to be more general than the traditional economist's "monetary" value), which will combine the values of the two services. The service set is largely determined by ecological factors while the value set is determined by socioeconomic factors. We combine the two by maximizing the ecosystem service with the value constraint, in a procedure that takes full account of both ecological and socioeconomic factors (see Figure 1 for an illustration).

All of this is obvious and evaluations had been underway for a while regarding various ecosystem services associated with coffee production on the island. And then Maria happened. This category 4 hurricane, undoubtedly so strong due to the elevated surface temperature of the surrounding ocean, itself a product of global climate change, ripped through the coffee production areas of the island, felling shade trees, stripping coffee bushes of their leaves, and destroying the infrastructure that is key to coffee production. The full extent of the damage is not known, and will not be fully evaluated for some time to come, but it is clear that this key industry has been dealt a significant blow.

While the damage to the industry is severe, to be sure, it is also clear that coffee will be an important element in the move to restore and improve Puerto Rico's general situation. Racked with debt, victim of colonial mismanagement for more than a century, with pollution and street crime epidemic, the problems were severe even before the hurricane. Now they seem insurmountable. Yet it is clear that part of the island nation's future lies with agriculture and a major, if not *the* major, component is agricultural production on coffee farms. Coffee had been and possibly will become again, the backbone of Puerto

https://doi.org/10.1111/nrm.12149

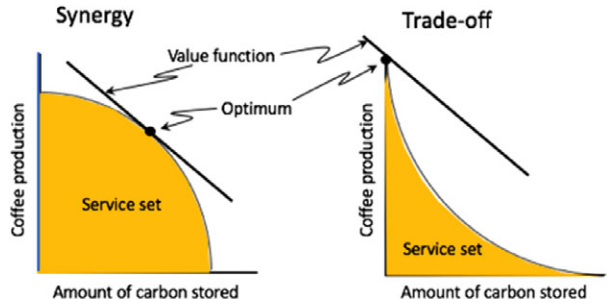

FIGURE 1 Illustration of the ecological service set optimized under the constraint of a linear value function (choice of carbon storage and coffee production are arbitrary—all other ecosystem services can be visualized with the same model framing, either two by two or in hyperdimension). Each point in the set represents the results of a particular management style (a) with a convex set, the optimal solution will be usually some management style that simultaneously seeks to optimize both ecosystem services, a "synergy" between the two services (b) with a concave set, the optimum will usually be pursuit of one or the other, but not both ecosystem services, a "tradeoff" between the two services

Rico's agrarian economy, but, more importantly, through its multifunctionality providing a host of ecosystem services, can be an important element of its post hurricane recuperation. And much of that will depend, I am certain, on how we conceptualize the construction of that new agrarian economy, a great part of which is dependent on the correct modeling framework, both analytical and metaphorical. Provisioning of ecosystem services with the goal of balancing tradeoffs and promoting synergies seems like a generally appropriate framework for modeling the system.

In particular, we envision five key services that become evident from both observation of the farms themselves, but also from informal interviews with coffee farmers. First is the question of production, which includes not only quantity, but in the case of a commodity like coffee, quality. Associated with this service is the multitude of other production on almost all coffee farms—plantains and bananas, yautia and malanga (key root crops in the traditional Puerto Rican diet), oranges and grapefruits, and many others. All represent production, and not all are amenable to simple evaluations based on simplified market assumptions. Second, the bees, butterflies, and other insects that pollinate the coffee (and some of the other relevant crops) provide an essential service. Although the arabica coffee that dominates the area is not dependent on pollination, its productivity has frequently been shown to increase with more pollination. Third, coffee is attacked by potentially hundreds of agricultural pests, from the coffee berry borer currently one of the main pests in the system, to the coffee rust disease, resulting from a fungus that over the past 5 years raged throughout Central America, but, for poorly understood reasons, left Puerto Rican farms relatively unscathed. Fourth, the trunks of the trees (and coffee bushes), their roots, and the extensive microbiome associated with soil processes on the coffee farms, provide an enormous storehouse of carbon, making coffee worldwide a most important system for future sequestration of carbon, a recognized emergency in today's world. Fifth, the biodiversity located in the former tropical forests of Puerto Rico flourishes in the traditional coffee agroforests. For example, the iconic Puerto Rican parrot, an endangered species, utilizes the traditional coffee agroforests, perhaps not for breeding, but as a way to get around between forest patches, and the culturally important coqui frogs are abundant in the traditional coffee farms.

How will these five key ecosystem services be involved in the re-emergence of the coffee economy of Puerto Rico? Have the services themselves operated in a way to make the whole system "resilient" in the face of the devastation of Hurricane Maria? Such questions are the base of current ongoing research in the system. In the end, we seek to know not only that that this agroecosystem may be resilient in the

face of catastrophic damage, but also what the mechanisms are of that resilience and to what extent we can anticipate the need for tradeoffs or take advantage of inherent synergisms.

John Vandermeer

Asa Gray Distinguished University Professor of Ecology and Evolutionary Biology, Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109
Email: jvander@umich.edu