Interactions of social, terrestrial, and marine sub-systems in the Galapagos Islands, Ecuador

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Galapagos is often cited as an example of the conflicts that are emerging between resource conservation and economic development in island ecosystems, as the pressures associated with tourism threaten nature, including the iconic and emblematic species, unique terrestrial landscapes, and special marine environments. In this paper, two projects are described that rely upon dynamic systems models and agent-based models to examine human–environment interactions. We use a theoretical context rooted in complexity theory to guide the development of our models that are linked to social–ecological dynamics. The goal of this paper is to describe key elements, relationships, and processes to inform and enhance our understanding of human–environment interactions in the Galapagos Islands of Ecuador. By formalizing our knowledge of how systems operate and the manner in which key elements are linked in coupled human–natural systems, we specify rules, relationships, and rates of exchange between social and ecological features derived through statistical functions and/or functions specified in theory or practice. The processes described in our models also have practical applications in that they emphasize how political policies generate different human responses and model outcomes, many detrimental to the social–ecological sustainability of the Galapagos Islands.

Galapagos Islands | human–environment interactions | dynamic systems model | agent-based model | process understanding

Within a global context, nearly all environments are impacted by humans, either directly and/or indirectly (1, 2). In the case of the Galapagos Islands, the use of land, water, and amenity resources by tourists, residents, communities, and other socioeconomic stakeholders must be balanced with the need for ecological protection to ensure the sustainability of iconic species, iconic landscapes, and ecosystem goods and services for future generations (3–5). The "Galapagos paradox" is often cited to describe the inherent conflicts between conservation and development, as residents flock to the Islands for jobs in tourism and tourists arrive to interact with nature, particularly, the iconic and emblematic species and unique landscapes and marine environments that have developed and evolved, at least partly, as a consequence of geographic isolation and available ecological niches for colonization (6–8). Designated as a World Heritage Site, a national park, and a marine reserve, the "specialness" that has contributed to the reputation of the Galapagos Islands for endemic and native species is the very condition that draws people to the islands, thereby threatening their existence and sustainability (9).

A fundamental question is how many people, that is, tourists and residents, exerting both direct and indirect impacts on a dynamic environment with feedbacks to the social subsystem, can the Galapagos support before the environment is severely degraded and the "golden apple" loses much of its luster and, hence, its global appeal. As such, the Government of Ecuador recently posed the question, "What is the carrying capacity of the Galapagos Islands?" In this paper, we focus on the processes that are embedded in our dynamic systems models (DSMs) as well as our agent-based model (ABM) to examine coupled human–environmental systems in the Galapagos Islands, and possible perturbations to them as a consequence of population–environment interactions and exogenous/endogenous dynamics.

The concepts of "value" and "risk" are central to a discussion about the "carrying capacity" of the Galapagos Islands and the direct and indirect impacts on ecosystem goods and services that are "consumed" in the Galapagos Islands (10, 11). As the social–ecological system evolves and adapts to internal and external tuning, island conditions may change, environmental quality may be socially redefined, and problems and challenges facing the social, terrestrial, and marine subsystems may be confronted through new and technological solutions, possibly involving transformative knowledges, participatory management schemes, and adaptive behaviors that attempt to reconcile the tensions imposed by the often conflicting goals of economic development and ecological conservation. Value pertains to the social–ecological importance of the Galapagos and the type of place that individuals as well as institutions want to have now and for future generations. As such, the international community is cognizant of the need for conservation–development strategies that are socially and ecologically sustainable. Risk pertains to the level of acceptable uncertainty and insecurity that are linked to the use and management of the Galapagos Islands. Risk can be viewed within the context of "acceptable" probabilities of change that are linked to threat levels and to the sustainability of the Galapagos. Threats to social and ecological systems may be associated with natural processes, such as El Nino Southern Oscillation events, as well as the direct and indirect consequences of the expanding human dimension, including, for instance, the possible grounding of ships carrying petroleum and other products to the Galapagos that are linked to the consumptive demands of a burgeoning human population. Therefore, value and risk are central propositions that guide the evaluation of the possible and acceptable alternate states and futures for the Galapagos.

There is no place on the Earth where this challenge is exemplified more strongly than the Galapagos Islands (12). Before 1968, there were no flights to the Galapagos Islands, getting there was possible only by boat. Tourism has grown dramatically in recent years, increasing more than threefold from 1990 to 2006 (13), with greater than 225,000 people visiting the islands in 2015, and the residential population now at ∼30,000. The increase

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in tourism, and attendant economic growth, has resulted in increased immigration. This interconnected growth in tourism and the resident population has created a commensurate, if not greater, strain on the support infrastructure and ecological resources of the islands (8). Although island sustainability is the general goal for conservation and development options in the Galapagos, the Galapagos vision and strategy for the future remains confounding and elusive.

Objectives and Approach

In this paper, we describe two projects conducted in the Galapagos that rely upon DSMs and ABMs to examine human–environment interactions. We use a theoretical context rooted in complexity theory to guide the development of our models and spatial simulations to assess processes and possible outcomes. Our models are data rich, statistically informed, calibrated and validated, and interpreted within empirical and theoretical contexts. The goal of this paper is to describe selected elements of our modeling projects to assess how they inform and enhance our process understanding of human–environment interactions. By formalizing our knowledge of how systems operate and the manner that key elements are linked, we specify rules, relationships, and rates of exchange between social and ecological features through derived statistical functions and/or functions specified in theory or practice. We draw insights from projects that addressed (*i*) decision-making processes in tourism using DSMs, and (*ii*) decision-making processes of fishers regarding alternate household livelihood strategies in tourism using an ABM.

DSMs manage complex feedback systems through the collection of interacting elements that function together in a specified system. Properties include quantities that vary over time, whose variability is described causally, and whose influences are contained within a closed-system feedback loop. The casual graph is augmented with information on stocks, flows, rates of change, feedback loops, and rules of behavior. Feedback loops are the key to understanding system dynamics as an initial cause can ripple through a chain of causation factors ultimately to "reaffect" itself. An ABM is a computational laboratory for experimenting with complex systems—sets of heterogeneous agents and frameworks for simulating each agent's decisions and interactions within a dynamic environment, responding to endogenous and exogenous forces, factors, and dynamics. Such systems evolve through time, using a description of the changing behaviors of individual agents and the environment that they engage through feedback mechanisms that link people and environment (14). ABMs focus on individual level behaviors with agent rules often based on theories of rational behavior and bounded rationality, but also able to explore alternate decision-making, learning, adaptation, failure, and change.

Our models maintain a focus on people, environment, socioeconomic conditions, and the support infrastructure that "conditions" the complex interplay between the consumptive demands of tourists and residents and the integrity of the natural capital of the Galapagos. We also focus on iconic species, iconic landscapes, ecosystem goods and services, and the environmental quality of terrestrial and marine visitation sites that are accessible by local residents and tourists. The advantage of our modeling approach is that individuals, households, nongovernmental organizations, and government entities are represented, feedback loops and critical thresholds are examined, allowing potentially nonlinear aggregations of micro behaviors to change larger social units such as communities, which, in turn, feedback onto micro behaviors at the individual and household levels (15). In addition, specification of nonlinear and complex underlying equations are permitted, and synergy, emergence, tipping points, and path dependence are accommodated (16, 17).

Study Area

Galapagos, a province of Ecuador, is 1,000 km from the mainland. For virtually everyone, the mode of entry or exit is by airplane, thus facilitating the effective monitoring of population movement into and out of the islands. The permanent population is small (~30,000 today), but growing and dynamic. There is no indigenous population, and in the first census in 1972, 3,488 residents, and in 1990, 10,000 residents were counted. Tourism is growing exponentially. In 2015, there were ~225,000 tourists who visited the Galapagos compared with ~65,000 in 2000 and ~40,000 in 1990. In addition, the likely effects of tourism are changing as an increasing share of tourists stay in hotels on land as opposed to sleeping on boats that navigate the islands. Day trips and island hopping has become the rule. The growth in tourism, especially land-based, in turn, has fostered increased migration by those seeking higher-paying jobs in tourism, construction, government, and related industries.

Island Biocomplexity

Island biocomplexity combines complex adaptive systems, including adaptive resilience, with a new island ecology that incorporates human induced change on the environment. Island biocomplexity encompasses the complex interactions within and among ecological systems, physical systems on which they depend, and human systems with which they interact (18, 19). Furthermore, complex systems focus on irreducible complexity arising from simplicity. This view sees the complex nature of systems as emerging from nonlinearities due to the large numbers of interactions involving feedbacks occurring at one or more lower levels within the system. Levin (20) defines complex adaptive systems through three properties: (*i*) diversity and individuality of components, (*ii*) localized interactions among those components, and (*iii*) an autonomous process that uses the outcomes of those interactions to select a subset of components for replication or enhancement. Ecosystems are complex adaptive systems because their macroscopic properties emerge from the interactions among the individual components of the ecosystem (21). Not only are biological components of ecosystems subject to selection, the macroscopic properties may feed back into the system and affect its future development.

Global changes, including the forces associated with tourism and migration, exert exogenous pressure on island ecosystems, but their systems have their own spatially contingent endogenous dynamics. Critical points in the spatial structure of patterns and feedbacks can produce a system with identifiable future alternative states in which instabilities can "flip" a system into another regime of behavior by changing the processes that control patterns. Dynamics emerging from local feedback mechanisms influence the evolving patterns and system behaviors and create emergence of new system structures that can vary across space–time scales (22). Bottom-up simulations involve autonomous agents as decision makers who interact with a dynamic environment and who learn and adapt to change (23). Defining the optimal scale at which processes function, recognizing the interactions among processes, and varying space–time scales as well as social–ecological hierarchies are a fundamental change in generating a richer understanding of pattern–process relationships using bottom-up models (24).

In the Galapagos Islands, human–environment interactions are fundamental to the complex interplay among the social, terrestrial, and marine subsystems. The pronounced social and ecological gradients that exist across the archipelago contribute to the creation of unique conditions that mediate ecosystem goods and services, including amenity resources, species diversity, and endemism. In addition, the expanding human dimension has created a diversity of social spaces as well as policies and programs developed to reconcile the many conflicts between resource conservation and economic development. Exogenous and endogenous dynamics, space–time lags, critical thresholds, feedback mechanisms, and adaptive behavior of agents are linked to changing social–ecological contexts and the coupled human–environmental systems that generate, influence, and sustain them.

DSMs: Tourism Management

In response to a request from the Government of Ecuador, system dynamic models of the Galapagos Islands (SDGI) were developed to examine human–environment interactions in the Galapagos and the direct and indirect effects of the expanding tourism dimension. The SDGI was designed to represent key factors and forces associated with coupled human–natural systems, linked to the tourism industry and the corresponding increase in the population who have come to the Galapagos for jobs in the burgeoning tourism industry. We describe the key elements of the SDGI in Table 1 using the overview, design concepts, and details (ODD) protocol described by Grimm et al. (25).

The SDGI models address hypothesized "slices" of the complex human–environment systems in the Galapagos. Through empirical evidence and theoretical guidance, we developed "storylines" that are used to create formal representations of human–environment interactions, judged to be most associated with the central question of the "carrying capacity" of the Galapagos. The models suggest a Galapagos that includes more urbanization, expansion of land-based tourism, and environmental change. Using stocks, flows, and rates of change, national and international tourism and land- and boat-based tourism are linked to examine the evolution of physical capital, social capital, and natural capital that are integrated and related to changes in ecosystem goods and services. Ordinary least-squares regression is used to link key variables, such as the number of tourists arriving in the Galapagos and the growth in the local population through the following equation:

$$Residents_y = 5{,}648 + \left(0.119912 * Tourists_y\right). \qquad [1]$$

Fig. 1 shows the number of tourists in the Galapagos, 1979–2012, and population projections for a series of scenarios and relationships that are embedded in our models—Moderate Growth, High Growth, Government Goal, Stagnation/Reorientation, and Collapse—generated for SDGI by R. R. Rindfuss and R. Tippett (Carolina Population Center, University of North Carolina at Chapel Hill, Chapel Hill, NC). Moderate Growth is calculated using a linear extrapolation model with the assumption that the number of tourists will change by the same number of persons each year in the future as the Average Annual Absolute Change observed over the base period. High Growth is calculated using a geometric extrapolation model with the assumption that the number of tourists will grow by the same average annual growth rate during each year in the future as it did over the base period. Government Goal ("Tourist Promotion 400K") assumes that the goal of 580,831 tourists is met by 2020, the distribution of tourists in 2020 is 67% foreign and 33% domestic, and the tourist amounts for 2013 through 2019 are calculated by linear interpolation. Stagnation/Reorientation projection is one in which tourism stagnates through 2015, experiences a few years of decline, and then begins to grow again: 2013 tourism is the average of tourist received in the Galapagos in 2011 and 2012 (182,930), tourism declines by 1% in 2014 and again in 2015, tourism declines by 10% between 2015 and 2016 and 5% between 2016 and 2017, rebounding with 8% growth between 2017 and 2018 and 4% growth between 2018 and 2019, and following 2019, tourism grows at the moderate growth rate from the linear growth through 2033. Collapse is based on the following assumptions: 2013 tourism is the average of tourists received in the Galapagos in 2011 and 2012 (182,930), tourism declines by 1% in 2014 and 2015, tourism declines by 67% between 2015 and 2021, distributed evenly across the 6-y interval, tourism doubles in 2022, but not at the levels seen before, and annual growth is 2% through 2033.

The primary variable driving the rapid resident demographic growth in the Galapagos is migration, with the overwhelming majority of migrants coming from the Ecuadorian mainland. Although a small number might migrate for work in fisheries or other economic sectors, tourism is the dominant engine driving the growth in the number of migrants, who come to work in businesses directly catering to tourists and in business/governmental jobs that have grown to support the increased number of tourists and residents. We further assume that future growth in the resident population will be tied solely to growth in tourism.

Historically, visitors experienced the Galapagos Islands by accessing the archipelago as boat-based tourists, generally sleeping and dining on-board and using tour guides to manage their access to sanctioned visitation sites across the islands. Boat-based tourists typically buy an all-inclusive cruise package and spend the main part of their experience on-board ship, generally consuming few urban facilities and services. Land-based tourists do not typically buy an all-inclusive package; they rely almost completely on local products, services, and labor. The numbers of domestic and foreign tourists are projected separately and subsequently separated in domestic boat-based and land-based as well as foreign boat-based and land-based, resulting in four main typologies of tourists used in our derived DSMs. Today, the number of hotel rooms exceeds the number of boat berths, and more hotels are being planned, further changing, the ratio of boat- to land-based tourism.

With nearly two million visitors arriving in the Galapagos since 2000, the tourism sector directly employs ∼60% of the residents (26) and it represents almost the entire economy. Due to its central role in the development of the Galapagos, the tourism industry is the driving force in determining the dynamics of change in all other employment sectors of the islands, particularly, generating high flows of migration from the mainland to the islands, increasing the introduction of invasive species, accelerating the consumption of resources, and increasing the pressure on basic services (27). Because of these factors, the SDGI uses trends in the number of tourists to project the impacts on linked social–ecological systems. In the SDGI, simple mathematical relationships represent the most relevant linkages among the social–ecological aspects of the Galapagos to describe potential scenarios of island sustainability.

To design and implement the SDGI, theory regarding the development of a tourism destination (28–30) was combined with systems theory and the technique of system dynamics simulation (27). This resulting theoretical framework describes the possible evolutions of social–ecological impacts related to the development of the Galapagos tourism industry (26, 27, 31). A demographic module was created, with projections generated to the year 2033, to represent the dynamics of the tourism industry and associated population growth through migration from the mainland. A module was also developed that examines the effects of population and tourism arrivals on linked social–ecological variables. The results of the models consist of simulations based on relationships in which time series data, conceptual links between variables, and derived mathematical functions among variables are used to assess human–environment interactions.

The demography and tourism component of the *SDGI* has at its core the interaction of people, both residents and tourists, and environment. The parameterization of individuals and household conditions and dynamics are informed by analyses performed using census data, park arrival information, and tourism exit interviews. Parameters include (*i*) demographic factors such as mortality, fertility, age and sex composition, migration and tourism visits; (*ii*) socioeconomic factors such as education, residence status, social networks, and wealth; (*iii*) biophysical factors such as area, biotic and abiotic characteristics, location, characteristics of environmental properties, ecological indicators, and the status of protected areas; and (*iv*) occupations and diversification strategies, composed of the conditions and dynamics of labor and agricultural markets bounded by relevant environmental and developmental policies.

This human component is focused mainly on (*i*) the role of the tourism industry and its associated set of services, (*ii*) how immigration is changing the economic constraints and opportunities of tourism, agriculture, and fisheries households, realizing that it is common for people in the Galapagos to work several jobs depending upon personal and occupational characteristics, and (*iii*) the "push" of agricultural and fisheries households by endogenous factors such as invasive species and the "pull" of the tourism sector as well as the influence of exogenous forces, such as El Nino events, on employment patterns and associated social–ecological conditions. The outcome of this component is the range of opportunities that economic sectors generate that are made available to local residents and tourists. The central actors in the Galapagos generate the following: (*i*) a labor market for different segments of the population, (*ii*) agricultural markets limited by the demand of agricultural products and the attributes of firms, and (*iii*) tourism firms creating construction demands and service jobs.

The ecosystem modification component addresses iconic species, iconic landscapes, and invasive species, and changes in ecosystem goods and services. For instance, when an agricultural household makes the decision to accept an off-farm employment opportunity or agricultural markets become more accessible, there is a direct consequence to land management practices (e.g., extensification or gradual abandonment of agricultural lands) and feedbacks between what happens on the land and future occupational decision-making in the other employment sectors. The type of agricultural management practices including land

Table 1. ODD for the system dynamic models of the Galapagos Islands

Variable	GF-ABM	SDGI
Type	ABM	DSMs
Purpose	Simulate the decision-making processes of Fishers in the Galapagos Islands with regards to employment choices and an alternate household livelihood strategy that would move those qualified into tourism (full- or part-time), given a variety of circumstances, desires, and personal characteristics.	Generate future scenarios of human–environment interactions with a particular focus on the forces of change in tourism and residential growth, environmental degradation, and household demographics and community infrastructure variables.
State Variable and Scale	Employment in Fisheries, Government, and Tourism Household Demographics and Change Household Expenses, Income, and Wealth Social Networks: Influence and Connectivity Fisheries Season for Lobster and Sea Cucumber Boat Access, Ownership, and Sailing Certification Individual and Household Levels	Invasive Species Number and Capacity of Terrestrial/Marine Visitation Sites Environmental Degradation Energy Consumption Land Use Patterns and Change Interisland Transportation Mainland-to-Island Transportation Hotel Occupancy Rate Community Infrastructure Archipelago Level
Process Overview and Scheduling	Time Step: Annual Updating Process: coupled human–natural systems to simulate decision-making processes of fishers relative to the pushes out of fishing and pulls into tourism and government employment, given expenses, income, wealth, and preparation for alternate employment possibilities.	Time Step: Monthly Updating Process: population growth, including natural residential growth and in-migration, drives changes in different components of the Galapagos social and environmental system, with community infrastructure, transportation, environmental quality, and household demographics affecting human–environment interactions.
Design Concepts	Human–Environment Interactions and Complexity Household Livelihood Theory Emergence of Employment Opportunities	Human–Environment Interactions Carrying Capacity Evolution of a Tourism Destination
Input Data	Household Survey Data Cadastral Data Number of Licensed Fishers Census Data at the Block Level Job Opportunities by Employment Sectors	Official Entry Form of Tourism 1979–2013 Census Data at the Block Level Urban Cadastral Maps Official Records for Energy Use and Waste Production Statistics on Transportation
Submodels	Demographic Change at the Household Level Employment Management Fisher Skills Change Number and Distribution of Jobs Fisher and Household Expenses, Income, and Wealth Fisher and Household Connectivity Through Social Networks	Invasive Species Capacity of Visitation Sites Environmental Quality and Degradation Energy Consumption Land Use Change Interisland Transportation Mainland–Islands Transportation Hotel Occupancy Rates
Reference	Walsh and Mena (7, 8)	Pizzitutti et al. (23)

abandonment and probable invasion emerge according to the attributes of the household and of the invasive species in a lattice that represents the plot of land. The human and ecosystem health component addresses links to (*i*) human impacts (e.g., runoff and wastewater discharge) on coastal environments, (*ii*) changes in the populations and patterns of iconic and emblematic species and their impacts on tourism, and (*iii*) adverse outcomes on human and ecosystem health from urbanization and consumptive pressures on ecosystem sustainability.

ABMs: Fishers and Livelihood Alternatives

Contemporary fisheries in the Galapagos is the product of the legacy of overfishing, when the lobster and sea cucumber fisheries were severely crippled through overexploitation (32). Some would argue that overregulation by the Galapagos National Park of boats, fishers, fishing grounds, seasons, and harvest quotes are also to blame for the decline in fisheries. Denkinger and Vinueza (33) examine the Galapagos Marine Reserve as a dynamic social–ecological system. Several authors examine fundamental elements of the marine reserve with a special focus on the local fisheries (34–37). Associated with the degradation of the fisheries industry in the Galapagos, tourism has expanded considerably, thereby creating economic opportunities for individuals, households, and communities. This ABM considers strategies of household livelihood alternatives in the Galapagos with the central proposition that fishers are being "pushed" and "pulled" into the tourism industry, but not all fishers are able to obtain alternate employment nor do all want to transition to full or part-time employment in nonfishing activities. The processes embedded in the model examine fisheries as a social–ecological system, where livelihood transitions are modeled and the multidimensional drivers of change are explored. Below, we highlight the structure of the model and the processes that drive model outcomes.

The Galapagos Fishers ABM (GF-ABM) simulates the decision-making processes of Fishers (Fisher agents) with regards to employment choices and an alternate household livelihood strategy that would move those most qualified into tourism, given a variety of circumstances, desires, and personal characteristics. We describe the key elements of the GF-ABM using the ODD protocol described by Grimm et al. (25) (Table 1). Fig. 2 shows the central elements of the model that are described below. The GF-ABM contains a demographic element that models basic changes at the Household level (Household agents). The model also contains an employment management component in which Fisher agents select jobs among three general employment sectors—fisheries, tourism, and government. The tourism and government sectors each have three tiers of jobs that require increasing agent skills. Fishers make their employment decisions based on their preference to remain in fishing, availability of jobs in the three employment sectors, and their personal/professional qualifications that facilitate their movement among the employment sectors. Households contain members that are non-Fisher agents, and Fishers belong to households. Income and expenses are calculated for Fishers and Household agents. The capitalized terms below highlight selected model components.

There are eight parameters related to demographic change and Fisher agent skills in the model: (*i*) Birth Rate—birth rate of 12.5 births per 1,000 individuals is used as the 2013 birth rate in the Galapagos Islands; (*ii*) Probability of New Household Members—probability that a new child will join the Household; (*iii*) Probability of a New Contributing Member—probability that a contributing member will join the Household each year; (*iv*) Probability of a New Non-Contributing Member—probability that a non-Contributing member will join the Household each year; (*v*) Minimum Wealth Needed to Obtain Sailing Certificate—dollar amount that a fisher's Household must expend to obtain a Sailing Certificate; (*vi*) Probability of a New Adult Registering as a Fisher—probability that a new adult member of a Household (i.e., a young adult who has turned 18 y of age) will register as a new Fisher and thereby become a new Fisher agent; (*vii*) Annual Increase in English Skill for Full-Time Work—English is set to the degree to which a Fisher's language skills will increase in 1 y of working in a full-time tourism job; the amount is modified by the percentage of time that a Fisher works in tourism; and (*viii*) Annual Increase in Sailor Skill for Full-Time Work—amount by which a Fisher's sailing skills will increase in 1 y of working in a full-time tourism level position; the amount is modified by the percentage of time that the Fisher is working in those jobs.

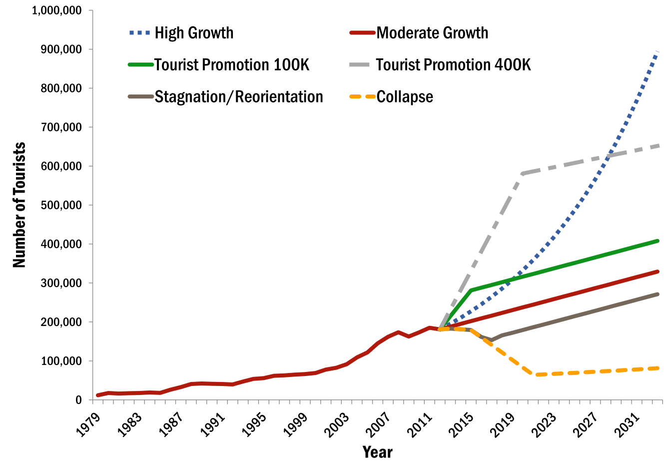

Fig. 1. Population projections for selected scenarios in the Galapagos Islands.

There are also 10 parameters that control the number and distribution of jobs in the fisheries, tourism, and government employment sectors: (*i*) Total Jobs Modifier—number of jobs that will be available to Fishers across the three employment sectors, multiplied by the number of Fishers and updated continuously as the model iterates; (*ii*) Distribution of Jobs among the Employment Sectors—three inputs control the distribution of total number of jobs in fisheries, tourism, and government that sum to 100; (*iii*) Distribution of Jobs in the Three Skill Levels—six inputs control the distribution of tourism and government jobs among the three job levels in each employment sector.

There are two parameters that control the likelihood that sea cucumber and lobster fisheries will be open in any given year, Probability of Open Sea Cucumber Fishery and Probability of Open Lobster Fishery that set the fisheries season.

There are six parameters that control various aspects of Fisher and Household agent income: (*i*) Average Annual Wages for Public Sector—dollar amounts that represent the average annual salary in the public sector to determine how much each non-Fisher, contributing, or college member of a Household earns each year; (*ii*) Average Annual Wages for Private Sector—dollar amounts that represent the average annual salary in the private sector to determine how much each non-Fisher, contributing, or college member of a Household earns each year; (*iii*) Percentage of Jobs in the Galapagos Islands; (*iv*) Percentage of Jobs on San Cristobal Island; (*v*) Percentage of Jobs on Santa Cruz Island; and (*vi*) Percentage of Jobs on Isabela Island.

There are eight parameters that describe expense aspects: (*i*) Sailing Certification Costs; (*ii*) Cost of Living per Adult; (*iii*) Cost of Living per Child; (*iv*) Cost of Living per College Student; (*v*) Cost of Switching Jobs, per Job Level Increase; (*vi*) Annual Boat Maintenance Costs for a Panga; (*vii*) Annual Boat Maintenance Costs for a Fibra; and (*viii*) Annual Boat Maintenance Costs for a Trawler.

Fisher and Household agents are created using an external text file that contains the characteristics of fishermen collected through a household survey conducted by Engie (38). In essence,

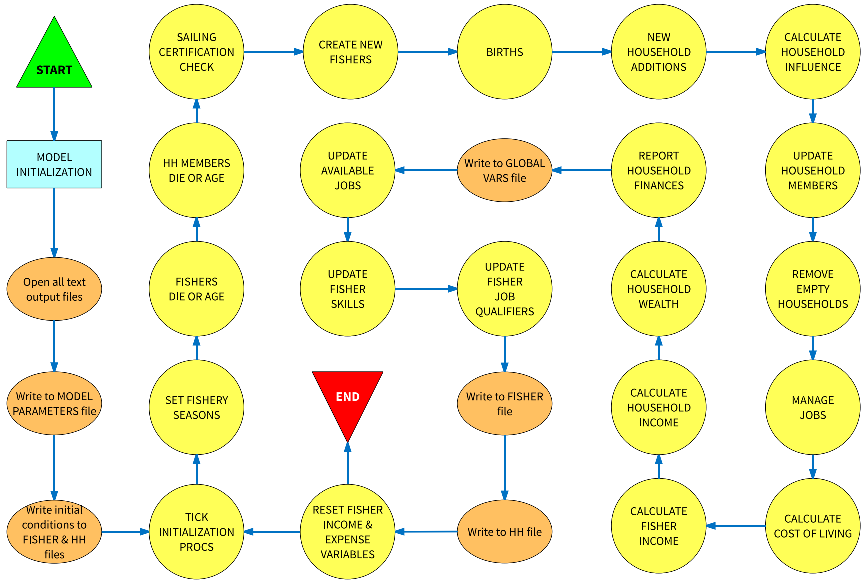

Fig. 2. Structural design and key elements of the Galapagos Fishers agent-based model (GF-ABM).

the initial conditions are one Fisher per Household. When the Fisher agents are created, those with a Sailor skill value of 50 or higher automatically receive their sailing certificate. If a Fisher owns a boat, the boat maintenance variable is set to the corresponding value among the three global variables based on boat type. Non-Contributing household members are those over 70 y old and who do not earn any income; Contributing members are adults between the ages of 18 and 70 who earn income; College Students are adults between the ages of 18 and 21 who are in college on the mainland and earn a fraction of their potential income; and Children are members under age 18 who do not earn income.

The influence variable is an index of the amount of influence a Household has in the community, and serves as a proxy for the Household's "connectedness" to individuals and organizations of power and authority. Adults over 45 y of age, both Fisher and non-Fisher members (both Contributing and Non-Contributing to Household income), receive an "influence" value of 1. Fishers and Contributing Adults (College Students are excluded) between 18 and 45 y receive a linearly weighted value ranging from 0 at 18 to 1 at age 45. The individual influence values of Fishers and Household members are summed and then multiplied by the influence modifier variable.

Household Cost of Living Variable is based on the number of adults in the Household, multiplied by the global variables that contain the annual cost of living per individual in each of the three categories (Contributing and Non-Contributing Adults, College Students, and Children). The Available Jobs Variable sets the initial number of available jobs in fishing and the three levels of tourism and government, multiplied by the seven global job variables that were initialized. Ten job variables are calculated: total jobs available; fishing jobs available; tourism jobs available; government jobs available; tourism levels 1, 2, and 3 jobs available; and government levels 1, 2, and 3 jobs available; set to 100% (i.e., 50%, 30%, 20% available jobs at the respective levels) to reflect the expected distribution of jobs, with fewer jobs available at the higher skill levels.

A series of functions and procedures operate in a designated order and repeat once for every annual iteration of the model. Of particular note is the Set Season procedure that is called at each annual iteration of the model to determine whether the sea cucumber and lobster fisheries are open. Open sea cucumber and lobster fisheries provide additional income to Fishers. Also, the Die-or-Age Fisher procedure performs a death check on every Fisher agent. Using each agent's age and sex, the corresponding mortality rate is retrieved from the age- and gender-specific mortality rate lists. If the Fisher dies, the model checks to determine if the Fisher owns a boat, and if so, the model calls to the Transfer-Boat-Ownership subprocedure.

The Sailing Certification Check procedure cycles through all Fishers who do not have a sailing certification and checks to determine whether one can be obtained. The Fisher's fishing preference is set to the highest of all other Fishers in the Household. If there are no other Fishers in the Household, then the fishing preference variable is set to a uniform random number ranging from 1 to 4, representing, respectively, a preference to decrease time in fishing and eventually to leave fishing entirely; a preference to decrease time in fishing, but remain in fishing; a preference to maintain the same amount of time in fishing as the previous year; and a preference to increase time in fishing.

The New Birth Check procedure performs a birth check on all Households. The Household agents are sorted by their agent number, and all of the female Contributing members in the Household between the ages of 18 and 40 are examined for the possibility of each agent having a birth. The New Household Additions procedure checks each Household for possible new nonbirth additions, considered to be relatives or current Household members. The Update Household Influence procedure updates the Household influence after all Fishers and non-Fisher members have died or aged and new members have joined the Household. The Update Household Members procedure updates the number of Fishers, Non-Fishers, and total number of members for all Households.

The Manage Jobs procedure allows every Fisher agent to select jobs each year, sorted randomly, to select the percent time in fishing, percent time in tourism, percent time in government, job level in tourism, and job level in government. The procedure also determines whether the Fisher will change his percent time in fishing if another job becomes available, depending upon job preferences.

The Calculate Household Cost of Living procedure updates the Household cost of living variable each year. The Calculate Finances procedure calculates incomes and expenses for Fishers and Households every year based on several factors: percent time in fishing, percent time in tourism or government, job level in tourism or government, open season on sea cucumbers and/or lobster, and boat ownership and boat type. The maximum possible tourism income is drawn randomly from a range linked to the job level. The maximum possible government income is a set salary linked to the job level. The Bonus Income from Sea Cucumber and Lobster Fisheries procedure is linked to the ability of fisheries to earn additional income in years in which Fishers can fish for sea cucumber or lobster. The Bonus Income from Boat Ownership procedure rewards Fishers who own boats.

The Calculate Household Income procedure calculates the income from the non-Fisher members of the Household, based on the number of Contributing and College members in the Household as well as the mean annual income and SD of annual income, Fishers income from all Fishers in the Household, Fishers of Households that own boats and earn additional income from the operation of the boat, as the Household manages the operation of the boat and earns a percentage of any income derived from its fishing activities.

The Calculate Household Expenses procedure calculates the total expenses for each Household every year from multiple sources: cost of living, boat maintenance, costs incurred from switching jobs, and cost of sailing certification. The Calculate Household Wealth procedure updates the wealth variable for each Household every year by taking the previous year's wealth value, adding the total household income, and subtracting the total household expenses.

Conclusions

The primary demographic variable driving the rapid resident demographic growth in the Galapagos has been migration, with the overwhelming majority of migrants coming from the Ecuadorian mainland. We assume that future growth in the resident population will be tied solely to growth in tourism. If tourism continues to grow at the pace of the past two decades, depending on the type of growth, in a few years there will be no open space to ensure that every tourist visiting the Galapagos experiences nature tourism at a high standard of quality. In parallel, social, administrative, and organizational systems in the Galapagos have not demonstrated the ability to evolve at the same rate that has seen the expansion of tourism, creating imbalances and failures as well as interactions that are negatively associated with the tourism sector and amplified for fragile and sensitive island ecosystems.

To understand social processes, we derived demographic projections of the expanding human dimension reflected through population census years, social survey, and focus groups. Population projections are used to forecast changes in tourism and residents according to defined scenarios of change. We also use social networks to create links of individuals and households to key actors and families. Core nodes in the social network represent ties to the director of the Galapagos National Park, mayor of the community, governor of the province, president of the fishing cooperative, and owners and managers of hotels and restaurants, and guides and managers linked to the airline and tourism industries. Empirically, we know that there exists four to five "power families" in our study area. We select some number of "power links" in the community and then randomize fisher connections over time. We also associate job switching from fisheries to tourism with English language skills. Education level, experience in tourism, and intention to leave fisheries are important factors in developing English language skills. We derived a function that determines the probability of increasing a skill based on age, education, and modify that probability based on their job and level of experience.

We have processed multidimensional data to derived mathematical functions that describe relationships among hypothesized variables and fundamental processes. We have done this through the development of DSMs and ABMs with the goal to not only create spatial patterns across space and time scales in the Galapagos, but to examine critical processes. Labor mobility through fishing to tourism was examined through alternate household livelihood strategies that were enabled by social connections, wealth, education, and retraining programs that strengthened weak human capital. Adapting to a smaller fishing footprint means accepting small, "purposeful" adjustments and more socially and politically "transformative" adjustments. Heterogeneous fishers, described through their beliefs, preferences, circumstances, social networks, and behaviors, provide the opportunity for a more nuanced examination of process relationships. Feedback mechanisms that link human behavior to environmental patterns and processes are complex, offer several measurement challenges, and may be scale dependent. The SDGI and the GF-ABM offer examples of how the formalization of knowledge through a diversity of measurement approaches might be integrated for a fuller understanding of social–ecological processes that shape and reshape coupled human–natural systems in the Galapagos Island and beyond.

Although the SDGI and the GF-ABM are different models that examine varying aspects of the Galapagos Islands, both use the demographic data and projections computed explicitly for the SDGI work and some of the computed functions between variables are used for weights and scores in both models, but they are not intrinsically linked for one model to nourish the other. The collected and derived data, however, support both models, although submodels vary according to modeling goals and intentions.

In sum, the social–ecological processes in our models are beneficial to understanding coupled human–natural systems in the Galapagos and beyond. For instance, examining feedback loops between people and environment, identifying critical thresholds and triggers, deriving statistical functions between key variables, assessing adaptation and learning, and integrating social networks and power relationships into our analyses combine in strategic ways to emphasize social–ecological processes that add richness to models and enhance understanding of how systems behavior relative to baseline conditions and scenarios of change.

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