Socio–environmental sustainability of indigenous lands: simulating coupled human–natural systems in the Amazon

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Understanding pathways to environmental sustainability in tropical regions is a priority for conservation and development policies. Because drivers of environmental degradation often occur simultaneously, a holistic approach is needed. We analyzed environmental degradation on demarcated indigenous lands in Guyana, using a spatially explicit, agent-based simulation model representing human livelihoods, forest dynamics, and animal metapopulations. We examined four plausible drivers of ecological degradation: conversion of land for agro–industrial use, erosion of hunting and dietary taboos, reduction in child mortality rates, and introduction of external food resources. Although social–ecological systems were resilient to internal changes, the introduction of external food resources resulted in large fluctuations in the system, leading to a deterioration in environmental sustainability. Our simulation model also revealed unexpected linkages within the system; for example, population growth rates of non-human animal species were related to the sustainability of human livelihoods. We highlight the value of simulation models as social–ecological experiments that can synthesize interdisciplinary knowledge bases and support policy development.

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Effective policies for development and conservation depend on understanding the mechanisms that underlie environmental sustainability (Foley *et al.* 2007). In the tropics, deforestation is often triggered by associated changes that occur simultaneously and interact with one another (Geist and Lambin 2002). Indigenous communities in contact with industrial societies often experience major transformations to their livelihoods, some of which may affect environmental sustainability. These changes are often the result of government interventions (Oliveira *et al.* 2007), dietary shifts (Kuhnlein and Receveur 1996), improved healthcare (Burgess *et al.* 2005), and technological advances (Jerozolimski and Peres 2003). Alterations to indigenous lands are also associated with these changes – for example, infrastructure development and participation in the market economy simultaneously affect deforestation on such lands (Oliveira *et al.* 2007). Factors potentially influencing sustainability must therefore be considered within the holistic framework of coupled human–natural systems (Liu *et al.* 2007).

We evaluated the effects of social–ecological changes on environmental sustainability within indigenous lands in the Amazon Basin that are undergoing rapid change (Luzar *et al.* 2012) by applying a simulation model that examines multiple factors that could potentially affect sustainability. Our spatially explicit model integrated changes in demography, forest clearing for agriculture, and wildlife populations resulting from habitat loss and hunting (Iwamura *et al.* 2014). We assessed sustainability in terms of resilience, which describes how well a system can transform itself to adapt to various perturbations (Scheffer *et al.* 2001). Considering the importance of indigenous people and their land for environmental management (Jerozolimski and Peres 2003; Oliveira *et al.* 2007), our findings have broad implications for sustainability in Amazonian systems.

Methods

Study area

The Rupununi region of southern Guyana in the Amazon biome (Figure 1) was an ideal location for developing this model because of the area's documented

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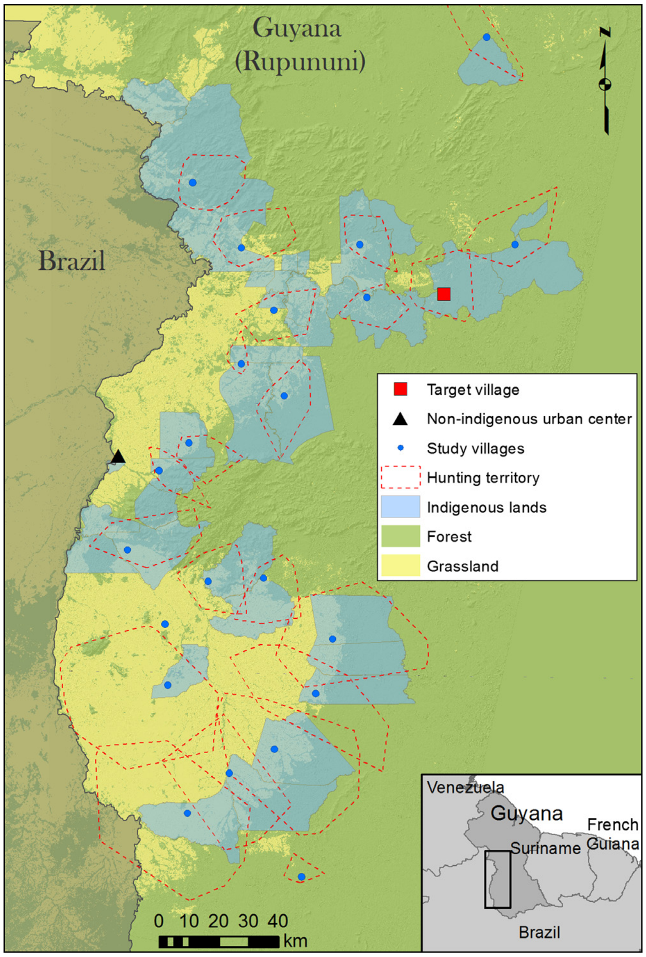

Figure 1. *Study villages in the Rupununi region of Guyana. The red rectangle shows the location of the target village; blue circles represent the locations of other villages where data were collected. The black triangle is the location of the only non-indigenous urban center in the Rupununi, the blue polygons delineate the boundary of areas titled to villages by the national government, and the red broken lines show village hunting territories. Background color indicates the type of land cover, based on Landsat TM images, with grassland represented in yellow and forest in green.*

retention of traditional practices in the face of socio-economic and land-use changes. The Makushi, Wapishana, and Wai Wai tribes indigenous to the region maintain traditional livelihood practices and subsistence activities, consisting primarily of wildlife hunting and cassava cultivation (Luzar *et al.* 2011). The Rupununi region has recently experienced major environmental and social changes as a result of governmental development initiatives promoting the integration of rural and urban areas. Indigenous communities live on titled lands that are smaller in extent than their traditionally occupied territory; surrounding areas, where the communities still hunt, are owned by the State and are subject to State management decisions (Figure 1).

Model description

Our study relies on a previously developed simulation model that uses an agent-based modeling (ABM) framework to represent social–ecological interactions in the Rupununi (Iwamura *et al.* 2014). ABM is a bottom-up approach that models the behavior of individual participants (hereafter called "agents", or autonomous decision making entities) and their collective influence on environmental change (Parker *et al.* 2003). The model synthesized demographic changes, hunting, farming, vegetation succession patterns, and animal metapopulation dynamics based on field data (Luzar *et al.* 2011; Iwamura *et al.* 2014). Remotely sensed images were used to produce a baseline land-cover classification, identifying forests, grasslands, cultivated areas, and water bodies. The model was constructed through the use of the NetLogo programming platform.

Our model contains four types of agents: indigenous households, villages, land-cover types, and animals (see WebPanel 1). Each household was modeled as an autonomous agent that converts forest patches into cultivated areas for crop production and that hunts animals for bushmeat to satisfy monthly caloric intakes. Household agents either satisfied minimum caloric targets and generated new households, or failed to meet the targets and disappeared from simulation runs. Village agents tracked the number of households and other aggregated variables. Land-cover agents controlled vegetation succession and habitat fragmentation, whereas animal agents followed metapopulation dynamics.

Environmental sustainability

Goodland (1995) defined environmental sustainability as a function of the "maintenance of natural capital". A simpler index, such as change in tree cover, is often used to measure environmental sustainability (eg Tilman *et al.* 2001). Here, we considered environmental sustainability in terms of resilience and ecological integrity (Scheffer *et al.* 2001), where social–ecological systems can cope with change while mitigating environmental damage. Our criteria for environmental sustainability considered whether (1) system outputs would attain alternative stable states, and (2) human and natural capital would avoid collapse. We measured these criteria based on the number of households present in a village, animal abundance, the number of vulnerable species in the village's hunting territory, and forest cover in the village's titled lands. A species is considered vulnerable when its population drops below 30% of its original level (following IUCN Red List criteria).

Scenario analyses

We applied the ABM framework to investigate four scenarios: (1) agro-industrial land conversion outside titled lands, (2) reduction of child mortality, (3) abandonment of taboos affecting hunting and dietary practices, and (4) introduction of external food. We selected one of the smallest and most remote villages out of 22 study sites (Luzar *et al.* 2011), because it has experienced little impact to date from the drivers of change examined in this study and is therefore appropriate for examining the impacts of future changes. We conducted 20 simulation runs of 250 years under the four scenarios.

Land conversion outside indigenous titled lands

Land surrounding indigenous titled lands in the Rupununi (Figure 1) is owned by the State and can be leased to agro–industrial enterprises. We assumed that land conversion would occur 100 years after village establishment. Four land conversion levels (25%, 50%, 75%, and 100%) were simulated, based on the hypothesis that a higher rate of land conversion outside titled lands would result in a greater decline in animal abundance; this was in accordance with the source–sink hypothesis of animal metapopulations, whereby populations in habitats with high mortality (due to disease, predation, or hunting) or insufficient resource availability for reproduction (sinks) maintain high numbers through immigration from nearby, high-productivity source populations (Pulliam 1998).

Reduction in child mortality rate

A greater number of government-funded medical clinics has led to a reduction in child mortality in the Rupununi, where the pre-adulthood mortality rate is currently 169 deaths per 1000 births (Wilson *et al.* 2006). We assessed the effect of child mortality on the system with rates of 0.1, 0.2, and 0.3 (corresponding to 100, 200, and 300 deaths per 1000 births, respectively). We hypothesized that lower child mortality rates would lead to increased population size and subsequently greater intensity of natural-resource extraction.

Change in adherence to taboos

Hunting and dietary taboos have long been observed among the indigenous peoples inhabiting the Rupununi; adherence to such taboos may weaken with increased contact with other belief systems (Luzar *et al.* 2012). An important taboo in the region is a partial prohibition on eating the meat of the gray brocket deer (*Mazama gouazoubira*). It is believed that this "master deer" species controls the movements of all deer species, and both the animal and its meat are associated with a spirit that is especially dangerous to children. We ran simulations based on the proportion of taboo adherents in a village, set at 25%, 50%, 75%, and 100% of the population. Limited data were available on the tabooed species; we therefore used data for red brocket deer (*Mazama americana*), which has similar life-history parameters (eg reproduction rate, habitat range). We hypothesized that if fewer people adhered to the traditional taboo this would result in higher rates of hunting of this species, with cascading effects on the populations of other species.

External food resources

Provision of external food resources to vulnerable families in remote communities is a common policy in indigenous lands; for example, conditional cash transfer programs such as Bolsa Verde and Bolsa Familia in Brazil provide money to poor families for the purchase of food (Kabeer and Waddington 2015). To date, similar programs have not been widely implemented in the Rupununi except in 2006, when severe floods destroyed much of the cassava crop. In our model scenario, external food was provided annually to support families unable to obtain sufficient calories from local resources alone. We varied the frequency of external food provisioning from 0 to 12 months per year. As supplemental food is only provided when a household is unable to support itself and is about to leave the area, we hypothesized that the provisioning of external food would stabilize the human population by reducing fluctuations in household number and natural resources.

Results

Land conversion

As predicted by the source–sink hypothesis, land conversion surrounding indigenous titled lands had negative impacts on animal populations and vegetation cover inside these areas. The "shock" of the conversion was eventually absorbed, however, and the system reached a new equilibrium (Figure 2a), although this depended on the level of land conversion. For 100% land conversion, the human population decreased from the original 50.3 households to 20.4 households, and animal abundance in the hunting territory dropped from 75.8% to 55.7% of its pre-village-establishment value.

We observed a threshold effect that caused a "tipping point" in the system, where human population and animal abundance at equilibrium became much lower at the 50% land-conversion level (WebTable 2). Human population and animal abundance near the village remained stable at conversion rates higher than 50%. Large animals with high intrinsic growth rates (eg lowland paca, *Cuniculus paca*) or that tend to congregate in herds (eg collared peccary, *Pecari tajacu*) were retained as important food resources (WebFigure 1). These species maintained stable populations during and after land-conversion events, either through higher growth rates

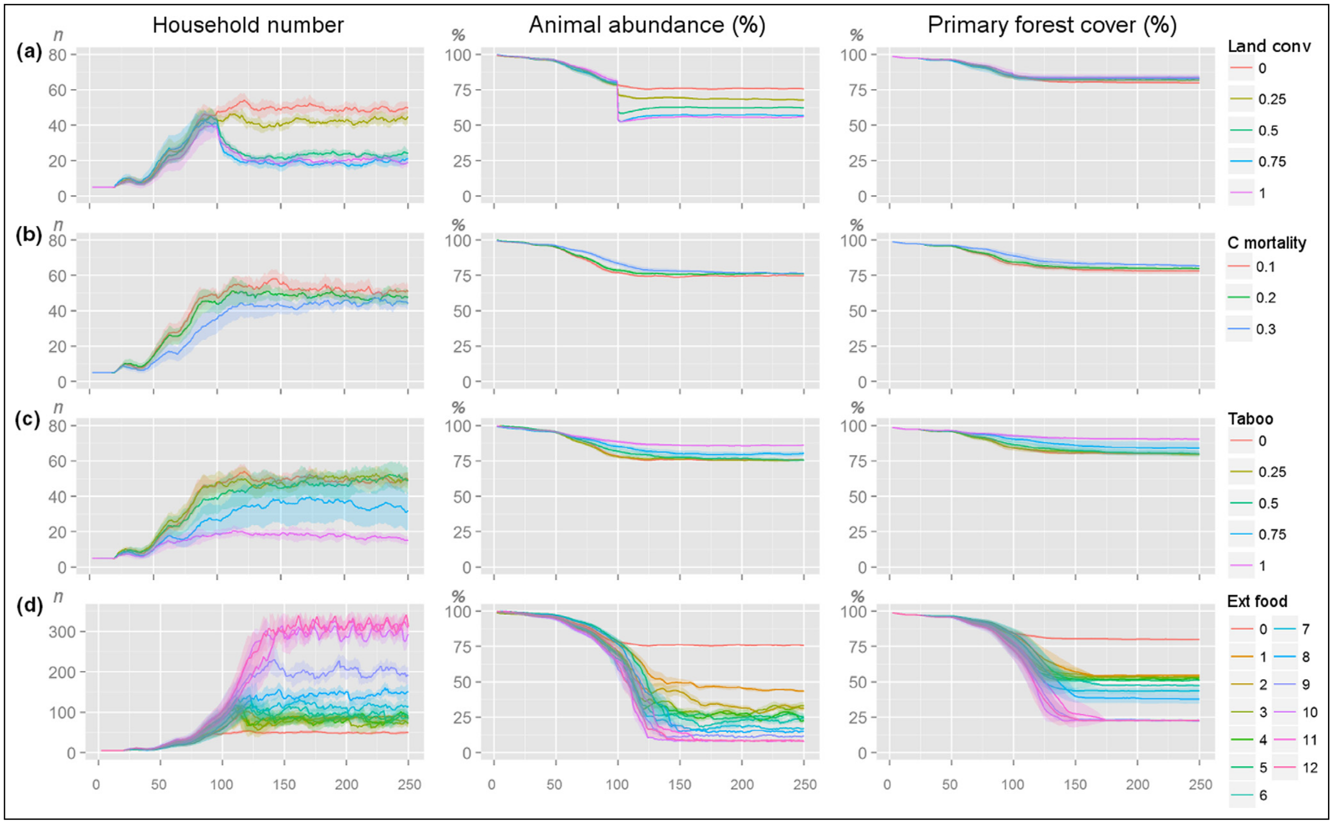

Figure 2. *Time series outputs from 20 simulation runs averaged for the four scenarios: (a) land conversion, (b) child mortality, (c) taboo adherence, and (d) external food introduction. Each row of graphs represents a scenario, and each column of graphs corresponds to a different simulation parameter being depicted. Time steps between 0–250 years since a village was established are depicted on the x axis of each graph; the y axis shows the simulation outputs. Solid lines indicate the average values of the simulation runs, and the pale shadow of the same color indicates 95% confidence intervals. Each color represents a set of simulation settings examined, as seen in the legend.*

or through greater use of heterogeneous habitats, as long as human population and hunting pressure were low enough to allow population replenishment.

Reduction in child mortality

Contrary to our hypothesis, the system reached a stable equilibrium under each of the child mortality scenarios, with no catastrophic environmental damage (Figure 2b). Lower rates of child mortality resulted in a larger human population, and consequently fewer animals and less primary forest cover (WebTable 2). However, environmental impacts were much lower as compared with other scenarios; higher population growth rates did not result in a "population explosion", because people emigrate from the village once they cannot obtain sufficient food to meet their energy requirements.

Change in adherence to taboos

Increasing the proportion of the population adhering to traditional taboos led to larger animal populations. Human population growth is lower where there are higher numbers of taboo adherents, which results in lower hunting pressure and higher primary forest cover. At intermediate levels of taboo adherence (50% and 75%), simulation runs produced one of two states: high human population and low animal populations and primary forest cover, similar to the 100% adherence case; or low human population and high animal populations and forest cover, as with the 25% adherence simulation (WebFigure 2). These two states resulted from a feedback loop: the human population becomes high (or low) after 125–150 years, followed by a low (or high) primary forest cover after 150–175 years, resulting in low (or high) animal abundance after 200–250 years (WebFigure 2).

External food resources

Contrary to our hypothesis, external food resources resulted in exponential growth of the human population, marked reductions in animal abundance and primary forest cover, and higher system instability. One month of food provisioning per year was sufficient to

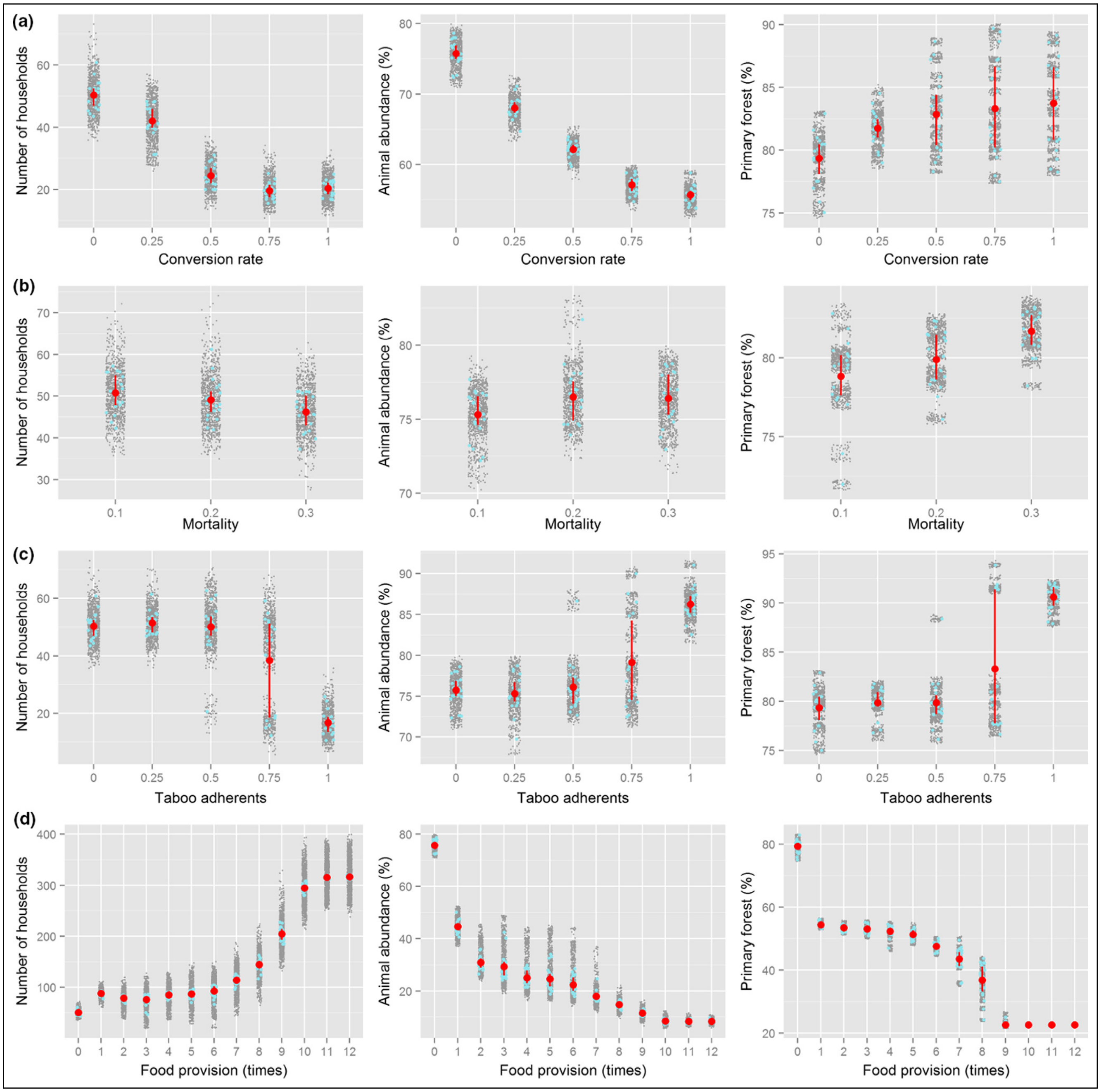

Figure 3. *Distributions of simulation outputs between 200–250 years. Outputs from 20 simulation runs for four scenarios: (a) land conversion, (b) child mortality, (c) taboo adherence, and (d) external food introduction. Gray dots represent the distribution of all the simulation outputs from every time step between 200 and 250 years; blue dots represent the averaged outputs for each of the simulation runs; red dots represent the overall average from these 20 simulation runs, with the bars indicating the 25% and 75% quartiles. Note: dots are horizontally distributed for display purposes only. The different levels of scenario settings are shown on the x axis, with the outputs (left: the number of households; center: the fraction of animal abundance remaining since village establishment within the hunting territory; right: the fraction of primary forest remaining since village establishment within a 6-km radius) shown on the y axis.*

triple the human population over 100 years and trigger large-scale instability in the system (WebTable 2). The human population continued to increase with up to 10 months of food provisioning per year (Figure 3b), at which point primary forest cover declined to less than 25% of its original extent and the animal population fell to about 10% of its original level (Figure 3b). Fluctuations in animal abundance and primary forest cover reached their peaks at the medium frequency of food provisioning (6–8 times per year).

Individual-agent variables revealed that external food became increasingly important over time relative to local food sources. Energy intake from bushmeat declined first, followed by a reduction in crop-derived energy (WebFigure 3). The human population grew rapidly as the dominant energy source shifted from local to external provisioning. Inter-household differences in farm size increased, indicating that families that survived food shortages in previous years subsequently cultivated larger areas. A shortage of farmland emerged when external food was provided 10 months per year (WebFigure 3); this shortage seems to limit human population growth.

Discussion

Our results show that an indigenous social–ecological system was resilient to changes in three factors (land conversion, demography, and taboo adherence), whereas a fourth scenario (the introduction of external food) was highly detrimental with regard to resilience. Thus, the dependence of human populations on local resources is important for maintaining the stability and resilience of social–ecological systems (Adger 2000). In our simulation, introducing external food weakened the reliance of the indigenous human populations on local resources and allowed for rapid population growth that, in turn, exerted higher pressures on both animal populations and forest cover. Widening the gap between population and available resources led to unstable boom-and-bust oscillations.

Negative impacts on the social–ecological system were observed even when resilience was maintained. Land conversion outside indigenous titled lands disrupted human and animal populations, and decreased forest cover, inside the titled lands. This perturbation was eventually absorbed, and the system shifted to another equilibrium, with lower human population, animal abundance, and forest cover. Impacts of land conversion were highly nonlinear due to the responses of animal populations to hunting pressure.

We found that food taboos suppressed human population growth, as suggested in previous field studies on the effects of taboo and nutrition intake (eg Spielmann 1989). Our results suggest that the impacts of taboo adherence depend on a historical chain of events, and are thus influenced by initial random fluctuations. A slightly higher human population due to stochastic events (eg hunting) can lead to reduced forest cover and lower animal abundances, which further affects hunting success, thereby creating a feedback loop. Such historical contingencies may explain why previous studies observed mixed effects as a result of taboo adherence (eg Colding and Folke 2001).

Demographic changes exerted fewer impacts relative to other stressors, as the model assumed household members will leave the area when they are no longer able to meet their food requirements. A high population growth rate alone was therefore insufficient to cause a population explosion. The dependence of the human population on local resources exerted a negative feedback; contact with external societies may weaken this dependence and increase emigration to urban areas. On the basis of household interviews extending over 3 years, Luzar *et al.* (2011) reported that 2.1 children per household left the community in the village closest to a non-indigenous urban center, whereas only 0.15 children per household emigrated from the most remote village.

Introducing external food eventually shifts energy dependence from local to external resources, causing a population explosion (WebFigure 3). In our scenario, this shift was accompanied by increased instability in environmental variables (WebFigure 3), similar to that found in phase shifts of ecological systems (Scheffer *et al.* 2001). The generated instability appeared to reflect small collapses among the human population due to severe food shortages that could not be compensated for by the provision of low levels of external food. Once external food became sufficient to support the human population, however, the number of households grew exponentially.

Given that ABM follows a bottom-up approach, information on micro-level processes influencing system dynamics can be observed (Parker *et al.* 2003). Under the external food introduction scenario, households that could not obtain sufficient bushmeat received external food to survive. During the following year, these families increased their farm size, eventually resulting in large differences in farm sizes among households (WebFigure 3); the resultant shortage of available land eventually became the limiting factor for the human population (WebFigure 3). Without this constraint, the population might have continued to grow, as has been observed in direct field studies in the Amazon (eg Sirén 2007).

Simulation models are simplifications of reality and their results should be interpreted with caution. We did not consider the possibility that indigenous people might change their behavior to reduce resource extraction; for example, they may stop hunting altogether if there is enough food to sustain the population. Moreover, food-aid programs are often linked with social policies intended to reduce the use of natural resources, for instance, by creating non-farm employment opportunities. This highlights the limitations but also the usefulness of simulation models as social experiments: they show what could theoretically occur by introducing external food without accompanying social changes.

In conclusion, coupled human–natural systems are highly complex and characterized by multiple feedbacks; managing for sustainability in such systems is challenging and necessarily adaptive. When applied and interpreted with caution, simulation models provide important insights that can reduce indirect negative consequences of management and improve its success.

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References

Adger WN. 2000. Social and ecological resilience: are they related? *Prog Hum Geog* **24**: 347–64.

Burgess CP, Johnston FH, Bowman DMJS, *et al.* 2005. Healthy country: healthy people? Exploring the health benefits of indigenous natural resource management. *Aust NZ J Publ Heal* **29**: 117–22.

Colding J and Folke C. 2001. Social taboos: "invisible" systems of local resource management and biological conservation. *Ecol Appl* **11**: 584–600.

Foley JA, Asner GP, Costa MH, *et al.* 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Front Ecol Environ* **5**: 25–32.

Geist HJ and Lambin EF. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* **52**: 143–50.

Goodland R. 1995. The concept of environmental sustainability. *Annu Rev Ecol Syst* **26**: 1–24.

Iwamura T, Lambin EF, Silvius KM, *et al.* 2014. Agent-based modeling of hunting and subsistence agriculture on indigenous lands: understanding interactions between social and ecological systems. *Environ Modell Softw* **58**: 109–27.

Jerozolimski A and Peres CA. 2003. Bringing home the biggest bacon: a cross-site analysis of the structure of hunter-kill profiles in neotropical forests. *Biol Conserv* **111**: 415–25.

Kabeer N and Waddington H. 2015. Economic impacts of conditional cash transfer programmes: a systematic review and meta-analysis. *J Dev Effect* **7**: 290–303.

Kuhnlein HV and Receveur O. 1996. Dietary change and traditional food systems of indigenous peoples. *Annu Rev Nutr* **16**: 417–42.

Liu J, Dietz T, Carpenter SR, *et al.* 2007. Complexity of coupled human and natural systems. *Science* **317**: 1513–16.

Luzar JB, Silvius KM, and Fragoso JMV. 2012. Church affiliation and meat taboos in indigenous communities of Guyanese Amazonia. *Hum Ecol* **40**: 833–45.

Luzar JB, Silvius KM, Overman H, *et al.* 2011. Large-scale environmental monitoring by indigenous peoples. *BioScience* **61**: 771–81.

Oliveira PJC, Asner GP, Knapp DE, *et al.* 2007. Land-use allocation protects the Peruvian Amazon. *Science* **317**: 1233–36.

Parker DC, Manson SM, Janssen MA, *et al.* 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. *Ann Assoc Am Geogr* **93**: 314–37.

Pulliam HR. 1988. Sources, sinks, and population regulation. *Am Nat* **132**: 652–61.

Scheffer M, Carpenter S, Foley JA, *et al.* 2001. Catastrophic shifts in ecosystems. *Nature* **413**: 591–96.

Sirén AH. 2007. Population growth and land use intensification in a subsistence-based indigenous community in the Amazon. *Hum Ecol* **35**: 669–80.

Spielmann KA. 1989. A review: dietary restrictions on hunter–gatherer women and the implications for fertility and infant mortality. *Hum Ecol* **17**: 321–45.

Tilman D, Fargione J, Wolff B, *et al.* 2001. Forecasting agriculturally driven global environmental change. *Science* **292**: 281–84.

Wilson W, Milner J, Bulkan J, *et al.* 2006. Weaning practices of the Makushi of Guyana and their relationship to infant and child mortality: a preliminary assessment of international recommendations. *Am J Hum Biol* **18**: 312–24.

Supporting Information

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