

ODD Protocol

This is a model description following the Overview Design Details (ODD) Protocol of Railsback and Grimm (2010) for the model used in M.A. Janssen and K. Hill (in review) An agent-based model of resource distribution on hunter-gatherer foraging strategies: clumped habitats favor lower mobility, but result in higher foraging returns, in *Simulating Prehistoric and Ancient Worlds*, Edited by J.A. Barceló and F. Del Castillo, Springer.

The first three elements provide an overview, the fourth element explains general concepts underlying the model's design, and the remaining three elements provide details. The model is implemented in Netlogo 5.0.4.

The model is a variation of Janssen, M.A. and K. Hill (2014) Benefits from grouping and cooperative hunting among Ache hunter-gatherers: Insights from an agent-based foraging model, *Human Ecology* 42(6): 823-835. The following changes are made:

- Import different distributions of vegetation maps. The code also includes the way we created the variations of the original maps. Since this was a time consuming activity we used saved maps for the sensitivity analysis.
- Alternative distributions of encounter rates among the vegetation types.
- Targeted movement of camps (in contrast to random movement).
- Adaptive decisions of camps, where camps stay at the same location if the average return rate per hunter passes a certain threshold during the previous day.

OVERVIEW

Purpose

The purpose of the agent-based computer simulation is to understand the basic rules of movement of hunters and camps and their consequences for cooperation and grouping patterns, given the prey and landscape dynamics that result in predicted hunting patterns that closely match the well-studied Ache hunter-gatherers of Paraguay. We assess model validity by comparing predicted distribution of harvested species and average meat caught per day to actual observed values among the Ache. Using these models, the impacts of group-coordinated movement patterns and pursuits are evaluated, and the sustainability of different hunter population sizes in the landscape can be explored. Finally we use the model to evaluate optimal group size and camp mobility for hunter-gatherers experiencing the ecological constraints specified in our model.

In this version of the model we explore the consequences of different distributions of resources, as well as different strategies of movement of camps.

State variables and scales

The model distinguishes agents and cells. Each cell represents a 100 meter x 100 meter area in a foraging landscape. Each cell has an assigned vegetation type, as well as corresponding information about prey encounter rates based on initial animal densities, harvest, reproduction, migration, and the recent passage of a hunter through the cell. The total landscape is 58,408 cells and is contained in a rectangular area of 217x313 cells (Figure S2).

There are two types of agents, namely hunters and camps. A hunter belongs to a specific camp, beginning at that location in the morning, and joining other hunters of his band at that location by the end of the day. Hunters move throughout the day. Camps may move once per day

or they may remain in the same spot. The movement of hunters is modeled at a 5-minute resolution. Hunters move/search or hunt/pursue prey. Prey can persist, be harvested by hunters, migrate, or reproduce. These events are reflected in the cell-specific probabilities of encounter for each prey species, which are updated at relevant time periods. When hunters kill an animal the availability of that species is reduced locally in the landscape immediately. Prey encounter rates also change each time unit on the landscape with the passage of a hunter regardless of whether a kill takes place (we call this “encounter suppression”). We assume that moving hunters frighten nearby game for some period after their passage, leading to decreased encounter rates of game along their path (see below for details). Finally, the model landscape cells undergo changes in probabilistic encounter rates due to prey migration and reproduction. In our model, prey harvest and removal from a cell can take place in any 5 minute period whereas migration happens only once every 3 months, and reproduction only once per year.

Process overview and scheduling

We present here a high level overview of the dynamics of the model. The details of the individual parts will be discussed later. At the beginning of the day the camp location for the end of the day is determined. Hunters initially move in the approximate direction of the camp for the end of the day. Every time step of 5 minutes an agent checks whether it is in a pursuit. If it is in a pursuit it remains in pursuit until the pursuit ends (a defined number of time steps for each prey type). If the hunter is not in a pursuit, it checks whether there is still time to search for prey. If so, the hunter can either turn or continue moving in his previous direction. There is a probability, p_s , that the hunter continues walking straight, and thus, $(1-p_s)$ probability that the hunter reorients. As the remaining time left in the day decreases, the hunter is more likely to reorient directly towards the next campsite. Pursuits are allowed to continue to termination near the end of the day even if this requires more time than the average model foraging day. Based on the amount of time the hunter has used on one day to arrive at the new camp, a new time budget is calculated for the next day to produce an average hunting time per day of 355 minutes.

Each time step an agent not in pursuit, and agent moves to a new cell and then checks the list of potential prey species in random order to determine whether it encounters a species in the cell it has entered. When a species is encountered, the agent decides whether to pursue, and upon pursuit, it terminates its search through the list of remaining potential prey in that cell. The decision to pursue is based on the expected return rate of the encountered prey type and the experienced return rates in previous days. If the agent is successful in its pursuit it will remove one animal from the landscape.

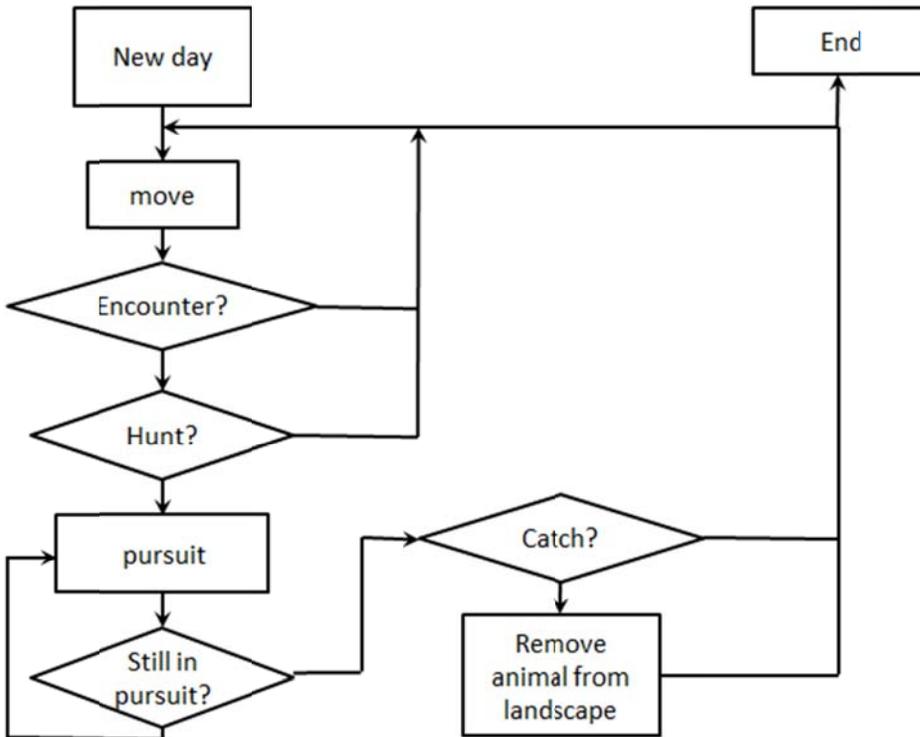


Figure S1: Flow chart of the model for one agent during one day. T is the time in minutes during the day. D is the duration of walking towards camp in minutes. W is a scaling parameter. The model is run in steps of 5 minutes for variable T .

Design concepts

Basic Principles: The modeling approach is based on the conceptual framework of Optimal Foraging Theory (OFT) and divides resource classes into habitats, patches and prey (Stephens & Krebs 1986). Habitats are geographical regions or techniques that lead to statistically constant encounter rates with specified prey and patches. Habitats do not deplete over the time scale relevant to daily foraging decisions and are hence characterized by a single average expected foraging return rate that can be compared to alternative habitats on any given foraging day. Patches are areas or techniques that contain opportunities for encounters with multiple prey often of different types. Unlike habitats, patches contain finite resources and show a temporal change in gain rate through time as a forager exploits the patch on the scale of minutes to hours. Patches are often partially exploited and then abandoned as their continuous gain rate declines over time. Unlike habitats or patches, prey are resources that cannot be partially harvested. Instead they are either acquired or not. Each prey type is characterized by an expected mean time of pursuit, and an expected mean success rate from pursuit. Thus prey have a single expected gain rate from pursuit (the probability of success times the mean food value obtained from a successful pursuit). Under these definitions, habitats and prey can be ranked according to expected gain rate upon encounter. Patches cannot be ranked because expected gains depend on how long the forager exploits the patch. In our model we ignore habitat choice and patchiness and instead focus on prey choice within a larger area that is treated as a single habitat. This is congruent with Ache conceptualizations of the decisions they face on a daily basis.

Adaptation, Objective and Learning: The agents have a fixed set of rules that determines what they do given the context of their environment. Based on encountering species hunters pursued, and if there are other hunters nearby they may join the pursuit for specific species. The rules do not change over time. The objective of the agent is to hunt for a specific time during the day based on the observed length of time Ache hunters hunt.

Prediction: Agents keep track of the success of hunting activities in the past weeks in order to evaluate whether they should pursue an encountered species. If the expected return of the species is higher than the experienced return they will pursue the species. The hunters also keep track of time during the day and how long it will take to return to the camp. Based on the time left during the day, the agents will move in the direction of the camp.

Sensing: The agents sense the cell on which they are located. They do not sense information on species of neighboring cells. Agents know the position of the camp relative to their current position.

Interactions: Hunters within a camp interact when they move through the landscape in a coordinated way since they try to stay near each other. When hunters encounter a species which can be hunted cooperatively those will join who are nearby and not pursuing anything else. Hunters also interact indirectly by removing animals from the landscape due to successful pursuits.

Camps interact indirectly only by harvesting animals from the landscape. When hunters from different camps encounter each other, they will ignore each other.

Stochasticity: Stochasticity affect choices on direction of movement of individuals and camps, encounters and success of pursuits, and the order in which hunter's decisions are updated.

Collectives: Camps consist of a number of hunters (default value five hunters) who start their daily hunting activities from the same location and in the evening come together again in the same location. When hunters hunt cooperatively, they only include hunters from their own camp even if hunters from other camps are nearby.

Details

Initialization

During the setup procedure of the model, the variables are initialized. Various accounting variables, such as lists of the number of animal caught, and group sizes during cooperative hunting are set to zero for all elements of the lists. The list of return rate over the past $R_D (= 20)$ days is set to 0.3 kg/hr, (lower than the long term return rate). As a consequence agents will be less likely to ignore encountered animals in the first few days of the simulation and more likely to ignore encountered prey as simulation proceeds. However, this has a negligible effect on the yearlong simulation runs employed here.

Model Input

Habitat types and prey densities

The model landscape consists of 58,408 one-hectare cells, which corresponds closely to the current area of the Mbaracayu Forest Reserve in Paraguay where ecological data were collected. This region of Paraguay is classified as Upper Parana Atlantic Forest, and constituted the last refuge of the Ache tribe in as the final band made permanent peaceful outside contact in 1977. Each 100x100 meter cell in the model was assigned a vegetation habitat type based on ground truth transects and subsequent supervised GIS classification with remote sensing using the Landsat 7 TM image with 6 optical bands and one thermal band (Naidoo and Hill 2006).

The assignment of a single vegetation type to each of the one-hectare cells in our model was the result of a four step process. First, our Ache research team walked nearly 11 million meters of random transect between 1994 and 2003. Each 200 meters they stopped and recorded, in their own language and according to their own classification, the forest type in which they were standing. Second, a subset of this ground truth data was used to train a computer algorithm to assign the vegetation types that corresponded to the reflectance values in 6 optical bands and one thermal band of the TM Landsat 7 TM imagery (see Naidoo and Hill 2006). Third, the computer algorithm was then checked by comparing predicted vegetation types in the remainder of the Mbaracayu reserve against the actual observed vegetation recorded by the Ache assistants on their transect inventories. Fourth, a successful computer algorithm then assigned a vegetation type to every 1 hectare cell in the entire Mbaracayu reserve area, and we used this as our landscape for the purposes of agent based modeling.

Methodological details (Naidoo and Hill 2006): We acquired a Landsat 7 TM satellite image of the Mbaracayu area from February 28, 2003. The image included the standard six optical bands (30-m resolution) and one thermal band (120-m resolution), all of which we used in our analyses. The image was georeferenced using a previously georeferenced Landsat image of the study area as a reference; the average RMS error (Root Mean Square error, a measure of the accuracy of the georeferencing) was 14.9 m. Of the 6129 transect units whose vegetation class was uniformly categorized by all five Ache field assistants, we randomly selected ~50% to be used in creating training fields for our supervised classification, with the remaining ~50% used in a post-classification accuracy assessment.

We delineated training fields on the Landsat image of Mbaracayu by visually inspecting color composites (a composite involving bands 1, 2, and 7, with a Gaussian stretch, was particularly useful) in combination with the homogeneous transect units selected for training. For each of the 7 vegetation classes, we created between 10 and 44 training fields, each having between 188 and 1285 pixels. We used the Multispec program to classify the image, using a maximum likelihood algorithm that assigns pixels to the class for which it has the highest probability of belonging. We assigned every pixel to a class, i.e., we did not set a threshold probability below which pixels were unassigned. As is typical in supervised classification procedures, we followed an iterative procedure whereby the accuracy of preliminary classifications was evaluated, training sites updated and improved, and new maps produced, until we arrived at a final classification. We then implemented a 3 · 3 majority filter and used this filtered classification as the final product of our analyses.

We assessed the accuracy of the final classification using the set of transects units held in reserve for this purpose. The class assigned to each transect unit by the classification was compared to the class assigned by Ache field assistants, and standard measures of comparison (producer's accuracy, user's accuracy, Kappa statistic) were produced to help interpret the

overall accuracy of the resultant vegetation map. We used a stratified random sampling design with 100 ground points for each category. Supervised classification of the seven vegetation classes resulted in an overall accuracy of 60.1% and a kappa statistic of 0.53 (Naidoo and Hill 2006). By calculating the number of cells classified for each category, and comparing these to the Ache's on-the ground classifications, we can determine the accuracy with which "true cells" were classified correctly (producer's accuracy), and the accuracy with which we expect classified cells to in fact be correct (user's accuracy). Producers accuracy ranged from 51% to 75%, whereas user's accuracy was more variable, ranging from 6.3% to 86.1%

Ache assistants distinguished 68 different vegetation types initially, but later Hill et al (1997) lumped these into 7 major habitat types easily distinguished by him and the Ache: 1) meadow/grassland; 2) large bamboo forest; 3) riparian forest; 4) high forest; 5) low forest; 6) small bamboo understory; and 7) liana forest. Each cell of 100x100 meter of our model foraging area was thus assigned a dominant vegetation type that corresponds to the habitat distribution in the current Mbaracayu Reserve. Figure S2 shows the vegetation landscape map used in our agent based model.

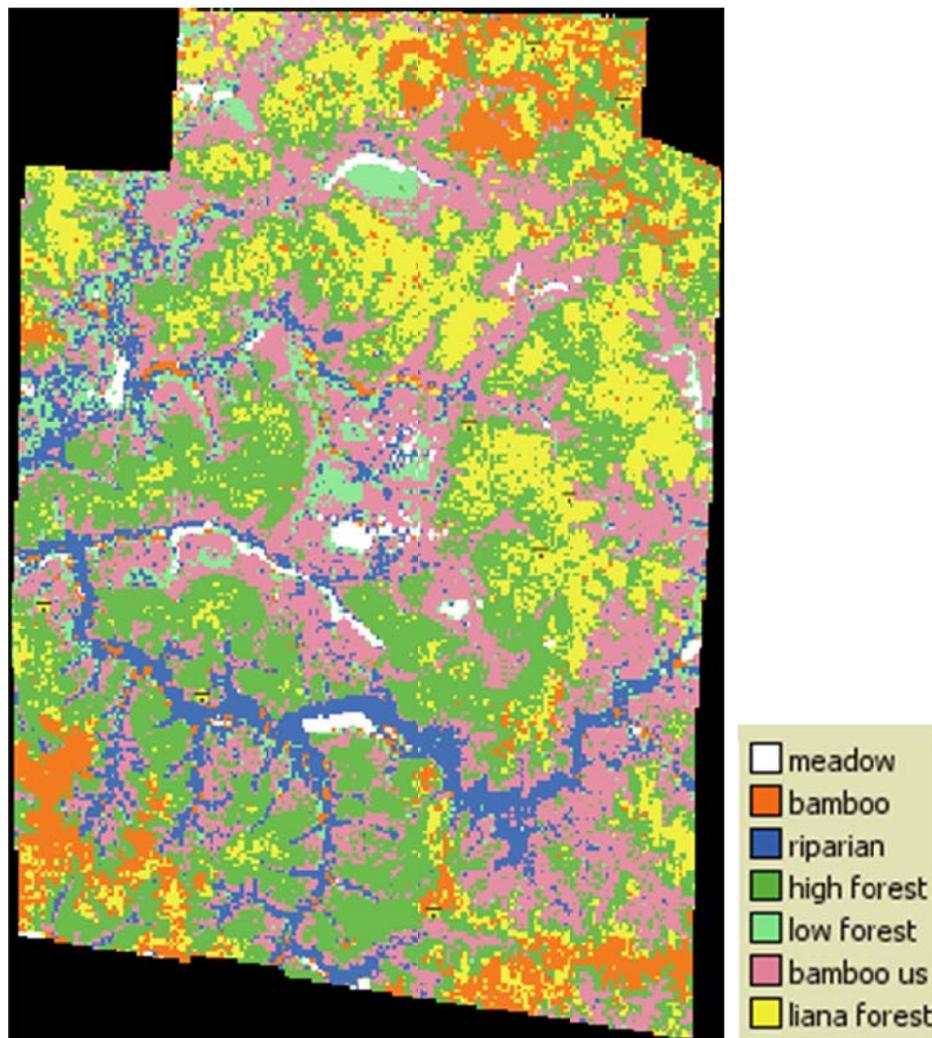


Figure S2: Netlogo screenshot of the model vegetation map (following the Mbaracayu Forest Reserve of Paraguay).

Vegetation types do not directly affect hunter or camp behavior in our model, instead they determine prey encounter probabilities. However, not all known prey species are added to the landscape. Over 500 edible vertebrate species inhabit the area, but most are rarely encountered or hunted and including them would lead to model complexity and a large increase in required computing power. Initially 10 prey species (Figure S3) were analyzed because each contributes at least 1% of the prey biomass to the Ache diet (Hill et al 2003). One species, nine-banded armadillo, accounts for 3 prey types because pursuits of fresh tracks, animals in a surface nest, and animals in a deep escape burrow, have different success rates and required extraction times and hence constitute different prey types from a modeling perspective. This means that the initial model had 12 prey types. In later versions of the model we included all 24 terrestrial vertebrate species that contributed meat to the measured harvest between 1994 and 2000 (Hill et al 2003). Again, because nine-banded armadillos constitute 3 prey types, we have a total of 26 prey types in the final model. The scientific identification of the prey species is indicated in Table S1.

Table S1. The 26 most commonly encountered prey types and the scientific name of each prey species.

Common Name	Scientific Name
Guan	Penelope superciliaris
Capuchin monkey	Cebus apella
9-B Armadillo nest	Dasyopus novemcintus
9-B Armadillo burrow	Dasyopus novemcintus
9-B Armadillo tracks	Dasyopus novemcintus
Red Brocket deer	Mazama americana
Coatimundi	Nasua nasua
Peccary (collared)	Tayassu tajacu
Tegu lizard	Tupinambis teguixin
Paca	Agouti paca
Tapir	Tapirus terrestris
Peccary (white lipped)	Tayassu pecari
King vulture	Sarcoramphus papa
Piping Guan	Pipile yakutinga
Howler monkey	Alloutta caraya
Naked-tail armadillo	Cabassous tatouay
Agouti	Dasyprocta azarae
Tinamou	Crypturellus obsoletus
Tayra	Eira barbara
Rabbit	Sylvilagus brasiliensis
Boa constrictor	Boa constrictor
Crab eating fox	Cerdocyon thous
Collared anteater	Tamandua tetradactyla
7-B armadillo	Dasyopus septemcintus
Black vulture	Coragyps atratus
RB toucan	Ramphastos discolorus

Mean observed encounter rates of each type within the different vegetation habitats is given in Table S2. Since these encounter rates are based on formal transect data collection we can compare them to actual encounter rates during hunting. For the 12 most common prey types the correlation coefficient of transect encounter rates and focal hunter encounter rates is quite high (Pearson's $r = 0.92$), indicating that transect data can be used to the expected encounter rates while hunting.

Rusty Guan		Collared peccary	
Capuchin monkey		Tegu lizard	
Nine banded Armadillo		Paca	
Brocket deer		Tapir	
Coatimundi		White-lipped peccary	

Figure S3. The ten most important prey species in the ABM Ache foraging model.

For each vegetation type in the landscape an expected prey encounter rate was calculated based on transect database tabulation. To accomplish this we simply calculated the total number of 200 meter transect segments that were reported by our research team to correspond to each vegetation type, and we divided this into the total number of encounters of each prey species that were encountered in those segments of the transects and then scaled this to get the encounter rate per 100 meters of walking. Importantly, the prey encounter rates are not based on a visual sighting but instead include only encounters that could feasibly lead to a pursuit (as defined by Ache hunters). An encounter does not take place if an animal is already fleeing rapidly when sighted, but it may take place if an animal is in a burrow, or heard in a thicket even when the actual body is not visible. In short, encounter rates in the model are those corresponding to real foraging choices, not simply animal density measures (Table S2). Vegetation specific encounter rates are tabulated and listed to produce prey encounter rates (encounters/100m) for each of the prey types considered in each of the cells of our model landscape (see Hill et al 2003).

Hunter and Prey Characteristics

A hunter is assumed to walk at a speed of 100 meters in 5 minutes regardless of vegetation type. This parameter is based GPS-measured walk speeds for Ache hunters during transect work (70 km walked in 58 hours) that averaged 1.24 km/hr through primary forest (no trails). Actual walking speeds during observed hunting ranged from 0.6 km per hour to 3 km per hour. The total time an agent hunts on average each day = 355 minutes. This mean hunt-day length is derived from focal hunter observations on a balanced sample of sunny and rainy days, published in Hill et al (1985) using only time spent searching for and pursuing prey (and waiting for hunters to arrive to a group pursuit). Basic characteristics of each prey item include mean weight of prey, mean pursuit time when a pursuit is attempted, and mean probability of a kill (success) for all pursuits attempted. Note that each different prey species is defined by a set of associated success rates and pursuit times. Hence a single species must be considered two different prey types if different types of encounters are associated with different expected average pursuit times and success rates. Measures of prey hunting parameters were extracted from our 1981-82 and 1997-98 focal man follow database (see Hill & Kintigh 2009).

The mean probability of a kill when a prey item is pursued, and the mean pursuit time after encounter were extracted from focal man data collected on 14 foraging trips from 1981-82 and 1997-98 (see Hill & Kintigh 2009). Mean weights have been previously published (Hill et al 2003). This database includes mainly pursuits by single hunters and some groups of two or three men. In some cases we observed the entire pursuit from start to finish, and have full data on pursuit times for all participants. In other cases we did not see the beginning or ending of a pursuit but were able to determine whether or not it was successful, hence the sample size for probability of a kill is often larger than that for mean number of minutes in pursuit. Finally, for rarer prey species no full pursuits were ever recorded, even though we observed partial or full pursuits "off the record". In these cases we assigned values based on our experience and on reports by Ache hunters who were consulted as we constructed the model (Table S3).

Table S2. Encounter rates of 26 prey types found in seven different vegetation habitats. The units are in number of opportunities for pursuit of the prey type per 100 meters walked.

	Meadow/ grassland	Bamboo forest	Riparian forest	High forest	Low forest	Bamboo understory	Liana forest
Guan	0.0031	0.0008	0.0028	0.0019	0.0029	0.0019	0.0026
Capuchin monkey	0.0016	0.0108	0.0072	0.0082	0.0050	0.0065	0.0094
9-B Armad nest	0.0101	0.0057	0.0098	0.0064	0.0075	0.0078	0.0053
9-B Armad burrow	0.0062	0.0037	0.0041	0.0031	0.0035	0.0041	0.0030
9-B Armad tracks	0.0388	0.0292	0.0480	0.0486	0.0505	0.0463	0.0370
Red Brocket deer	0.0008	0.0008	0.0003	0.0014	0.0006	0.0009	0.0011
Coatimundi	0.0016	0.0012	0.0007	0.0008	0.0003	0.0006	0.0013
Peccary (collared)	0.0000	0.0003	0.0011	0.0005	0.0002	0.0003	0.0001
Tegu lizard	0.0000	0.0005	0.0002	0.0004	0.0008	0.0006	0.0005
Paca	0.0039	0.0008	0.0029	0.0022	0.0024	0.0029	0.0005
Tapir	0.0000	0.0008	0.0012	0.0005	0.0008	0.0004	0.0005
Peccary (white lipped)	0.0008	0.0023	0.0023	0.0023	0.0041	0.0022	0.0033
King vulture	0.0000	0.0000	0.0000	0.00012	0.0000	0.00009	0.00007
Piping Guan	0.00155	0.00092	0.00064	0.00065	0.0000	0.00074	0.00112
Howler monkey	0.0000	0.00015	0.0000	0.00010	0.0000	0.0000	0.0000
Naked-tail armadillo	0.0000	0.0000	0.0000	0.00017	0.0000	0.00003	0.00007
Agouti	0.0000	0.0000	0.00042	0.00038	0.00015	0.00028	0.00046
Tinamou	0.0000	0.00062	0.00021	0.00012	0.0000	0.00003	0.00020
Tayra	0.0000	0.0000	0.0000	0.00012	0.0000	0.00012	0.00013
Rabbit	0.0000	0.0000	0.0000	0.00021	0.0000	0.00003	0.0000
Boa constrictor	0.0000	0.0000	0.00032	0.00014	0.0000	0.00006	0.0000
Crab eating fox	0.0000	0.0000	0.0000	0.00005	0.0000	0.0000	0.0000
Collared anteater	0.0000	0.00015	0.00011	0.00000	0.0000	0.0000	0.0000
7-B armadillo	0.00078	0.0000	0.00011	0.00000	0.0000	0.0000	0.00007
Black vulture	0.0000	0.00015	0.00011	0.00014	0.00015	0.00018	0.0000
RB toucan	0.0000	0.0000	0.0000	0.00000	0.0000	0.00003	0.0000

Table S3. Sample size (observed hunts) for measures of pursuit time and probability of success.

	Pursuit time	Success rate
Guan	7	48
Capuchin monkey	59	67
9-B Armadillo nest	40	84
9-B Armadillo burrow	16	18
9-B Armadillo tracks	31	31
Red Brocket deer	8	33
Coatimundi	28	28
Peccary (collared)	7	23
Tegu lizard	9	41
Paca	116	104
Tapir	10	10
Peccary (white lipped)	109	128
King vulture	estimate	estimate
Piping Guan	same as guan	same as guan
Howler monkey	same as capuchin	same as capuchin
Naked-tail armadillo	same armad. nest	same armad. nest
Agouti	estimate	estimate
Tinamou	same as guan	same as guan
Tayra	estimate	estimate
Rabbit	estimate	estimate
Boa constrictor	estimate	estimate
Crab eating fox	estimate	estimate
Collared anteater	same as capuchin	same as capuchin
7-B armadillo	same armad. nest	same armad. nest
Black vulture	estimate	estimate
RB toucan	same as guan	same as guan

Table S4 presents the basic foraging parameters pursuit time and success rate for single hunters, as well as the mean weight of prey. Pursuit times are rounded to five-minute intervals in order to conform to the duration of one time step in the agent-based model.

Table S4. Hunting related data for single hunters on 26 prey types.

	Pursuit time (minutes)	Success rate (probability)	Weight (kg)	Encounter suppression
Guan	5	0.0625	0.8	0.6
Capuchin monkey	55	0.7	2.3	0.1
9-B Armadillo nest	10	0.276	3.8	0.8
9-B Armadillo burrow	25	0.33	3.8	0.9
9-B Armadillo tracks	5	0.032	3.8	0.6
Red Brocket deer	10	0.18	25.8	0.4
Coatimundi	10	0.643	3.5	0.1
Peccary (collared)	40	0.26	16.3	0.4
Tegu lizard	30	0.61	2.3	0.9
Paca	10	0.106	6.7	0.8
Tapir	40	0.05	177	0.4
Peccary (white lipped)	120	0.192	24.9	0.1
King vulture	10	0.05	2.4	0.6
Piping Guan	5	0.0625	1.78	0.6
Howler monkey	55	0.7	4	0.1
Naked-tail armadillo	10	0.276	4.87	0.8
Agouti	30	0.7	1.8	0.6
Tinamou	5	0.0625	1.1	0.6
Tayra	30	0.25	3.2	0.6
Rabbit	5	0.1	1	0.6
Boa constrictor	5	0.8	8	0.9
Crab eating fox	10	0.1	4.8	0.4
Collared anteater	55	0.7	1.6	0.8
7-B armadillo	10	0.276	1.28	0.8
Black vulture	10	0.05	1.6	0.6
RB toucan	5	0.03	0.4	0.6

Group hunting

Ache hunters often call for help and engage in cooperative pursuits of some key prey species. We therefore constructed a model that allows us to examine the effects of cooperative hunting and the formation of pursuit group sizes greater than one individual. In order to assess the economic implications of cooperative pursuits we also estimated the effect of pursuit group size on success rate and mean pursuit time per hunter. This calculation follows Hill and Hawkes (1982) but uses data from all directly observed pursuits from 1980-1997 when the full number of participants was recorded. We proceeded in three steps: 1) We plotted mean total kilograms acquired and mean total hunter minutes in pursuit, by pursuit group size. These were assumed to be monotonically increasing functions, and were fit with either linear or non-linear regression by whatever function (power, exponential, polynomial) gave the highest r-squared value (see Table S5). 2) We used the regression function to produce a predicted (smoothed) relationship between total harvest and total pursuit minutes and pursuit group size (Figure S4). We then divided this by the number of hunters in the pursuit group to get per capita values of mean prey weight obtained per pursuit and mean minutes expended per pursuit, for observed pursuit group sizes. 3) Finally, we divided each value by the value at pursuit group size of 1 to get relative success

rate and relative pursuit time for groups of each size. These numbers were then multiplied by the values for single hunter pursuits in Table S4 in order to estimate expected pursuit time and success rate per hunter at various group sizes (Table S6). The numbers match well with our impressions from observing hunts and our casual guesses about relative success and pursuit group time for groups of various sizes. Based on the well-predicted pursuit parameters as a function of pursuit group size we can be fairly confident of the values associated with group hunting for most of the species in our model. Only the success rate from cooperative peccary hunts is still not well measured due to high sample size and high variation between hunts.

Table S5. Correlation coefficients of the regressions used to estimate the relationship between pursuit group size and parameters used in the cooperative hunting model.

	R ² total pursuit time	R ² total harvest
Capuchin monkey	0.88	0.98
9-B Armadillo nest	0.41	0.99
Coatimundi	0.95	0.85
Paca	0.88	0.78
Peccary (white lipped)	0.62	0.15

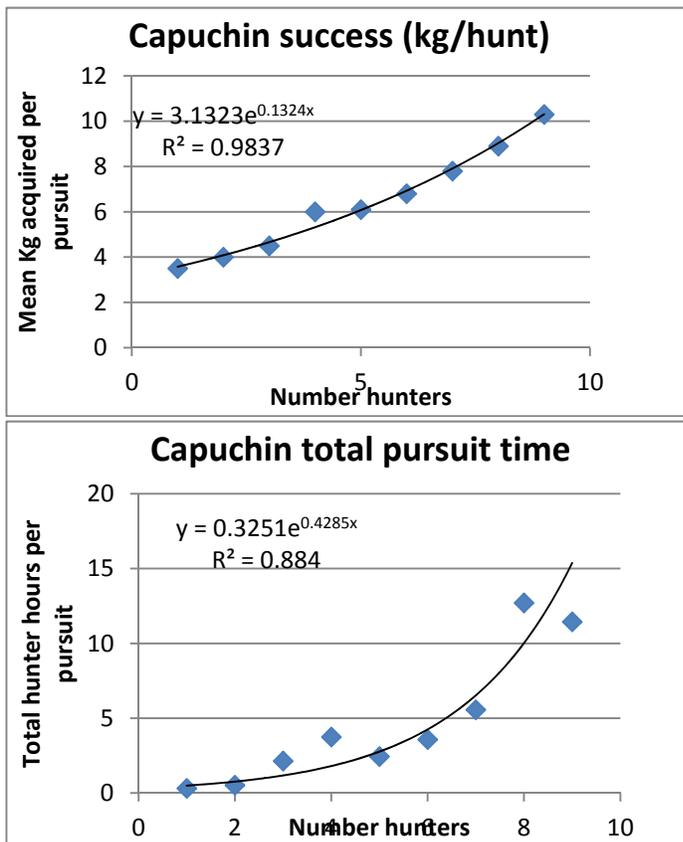


Figure S4. Example of the regression based smoothing procedure used to estimate the relationship between pursuit group size and total minutes of pursuit (top) and mean total kg harvested (bottom) for hunts of capuchin monkeys between 1980-1997.

Ache hunters generally share prey amongst all band members present in a camp (Kaplan et al 1984). This presents a potential conflict between the goals of maximizing individual hunting return rates, or maximizing the food that will be consumed by band members. We note that the expected return rate upon encounter for pursuit of two prey types (capuchin monkey and coati) decreases monotonically as group size gets larger (Figure S5).

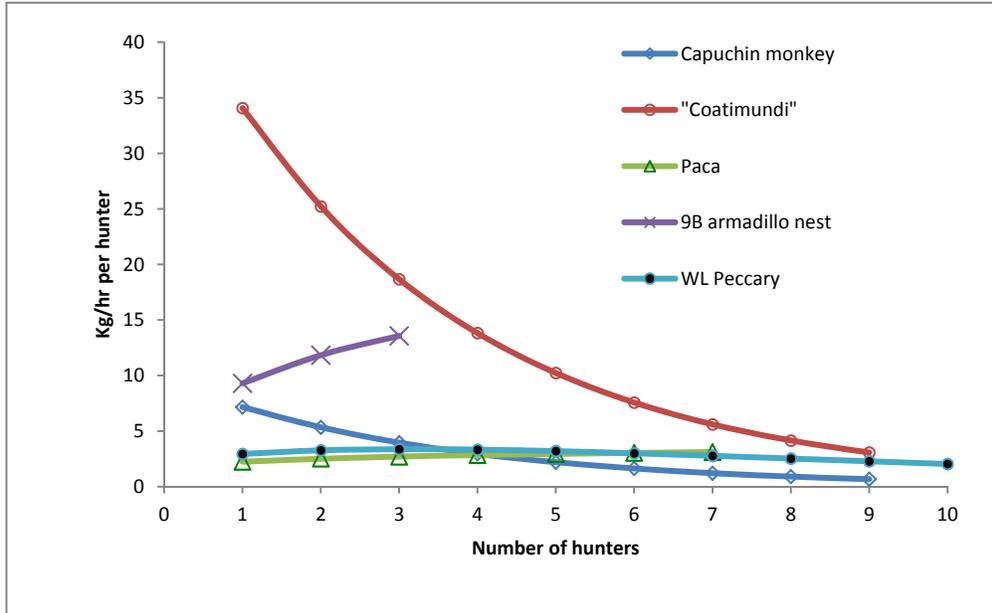


Figure S5. Return rate per hunter for pursuits with five prey types as a function of number of hunters who participate in the pursuit event. For some species, hunters who call for help lower their own expected returns, whereas for other species the hunter who encounters a prey item can expect higher individual success if he calls for others to help him.

Hence individuals seeking to maximize their own hunting return rates might not want to call for help in a pursuit. However the mean return rate per hunter, at even the largest pursuit group sizes is still well above the overall expected mean foraging return rate of hunters who are searching (approximately 0.5 kg per hour, Hill and Kintigh 2009). This means that monkey and coati hunters could maximize their own return rate by pursuing the prey alone, but that if food is shared, the group meat consumption rate will be increased by calling for companions to join a pursuit (see Smith 1985 for a discussion on the distinction between “members vs. joiners rules” for optimal pursuit group size). For the other three species (paca, armadillos, peccaries), pursuit group sizes above one hunter lead to higher return rates for all participants. Thus, individuals who encounter these prey should be expected to call for others to join a pursuit regardless of whether their goal is to maximize their own individual hunting return rate, or the daily food consumption rate of members of their residential band (including themselves).

Table S6 presents the data for the pursuit times and success rate for different group sizes of cooperative hunting events for five important species in the model. Other species are either not cooperatively hunted or we have no information that allows us to construct the relationship between pursuit group size and relevant parameters of the hunt.

Table S6: Success rate and pursuit times for different group sizes during cooperative hunting events on five cooperatively pursued species.

# hunters	1	2	3	4	5	6	7	8	9	10
	Pursuit time (hours) per hunter per pursuit									
Capuchin	0.900	0.691	0.707	0.814	0.999	1.278	1.682	2.258	3.081	
Coatimundi	0.130	0.109	0.121	0.152	0.204	0.284	0.408	0.597	0.888	
Paca	0.200	0.274	0.330	0.376	0.417	0.453	0.486			
9-B armad	0.136	0.084	0.066							
WL Peccary	2.000	1.221	0.994	0.910	0.889	0.905	0.947	1.012	1.098	1.207
	Success rate (mean kills) per hunter per pursuit									
Capuchin	0.700	0.400	0.304	0.260	0.238	0.226	0.221	0.221	0.224	
Coatimundi	0.643	0.398	0.329	0.305	0.303	0.312	0.332	0.359	0.396	
Paca	0.106	0.163	0.210	0.252	0.289	0.324	0.357			
9-B armad	0.276	0.216	0.196							
WL Peccary	0.192	0.130	0.109	0.099	0.093	0.089	0.086	0.083	0.082	0.080

Prey population dynamics

Animal populations in a particular region are affected by four processes that add or subtract individuals to the landscape. These are births and immigration (adding individuals), and deaths and emigration (subtracting individuals). In order to estimate the effects of human harvest on the primary prey species in the model we make the simplifying assumption that all deaths are due to human hunting. Migration into relatively empty cells, from cells with higher prey densities is allowed and modeled by simply redistributed animals into neighboring cells once every three months. This allows depleted areas to recover according to the biological characteristics of each species. Death of a single animal takes place each time a hunt is successful (determined probabilistically according to values on Tables S4 and S6). The model presumes that a number of cells that are vacated after an animal has been killed: this area is calculated as the reciprocal of the transect-based estimated densities per hectare per vegetation type for each species (Table S7). After a kill we clear encounter rates of the cells around the location of the capture until we reach a total of one animal being removed from the landscape. Migration takes place every 3 months and is explained in the next section below. In addition, each year we assume that reproduction takes place in the population in a density dependent fashion. Reproduction is assumed to be density dependent and follow the logistic growth model where changes in population size (prey density in a cell) at each time interval are calculated as:

$$\frac{dP}{dt} = r_{\max} P \left(1 - \frac{P}{K} \right)$$

The carrying capacity (K) of each cell is presumed to be the initial density of animal species as measured in the transect study for regions that are rarely or never hunted (the vast majority of the Mbaracayu reserve). It should be remembered that the encounter rates reported in Table S2 are taken as direct indicators of population density and are assumed to represent K, however these encounters represent only animals that were detected and could be pursued. This is likely to produce an underestimate of the true number of animals in an area, and hence addition of

individuals through reproduction in our model may underestimate actual biological reproduction for these species (because the annual reproductive rate is multiplied by the density estimate in order to calculate reproductive augmentation of the densities each year). The evaluation of sustainability is thus conservative, since the true breeding population for many species is probably substantially higher than the estimate derived from encounters with animals that could be hunted. Density independent reproductive rates are published for most of the species in our study, and can be estimated based on body size for the remainder (Robinson and Redford 1986) (Table S7). Some of the minor prey species were simply assigned r_{\max} values from similar species in our 10 important prey with known values. Carrying capacity is assumed to be equivalent to the equilibrium baseline transect density estimates measured for each species. Encounter rate and prey density per hectare are assumed to be proportional in this model.

Table S7. Data for population dynamics: The fraction of an animal removed from the landscape by setting the probability of encounter to zero for one cell of a vegetation type.

	Meadow/ grassland	Bamboo forest	Riparian forest	High forest	Low forest	Bamboo understory	Liana forest	Density independent growth rate (r_{\max})
Guan	0.1064	0.0275	0.0961	0.0652	0.0996	0.0652	0.0893	0.15
Capuchin monkey	0.0686	0.4630	0.3086	0.3515	0.2143	0.2786	0.4030	0.14
9-B Armad nest	0.4512	0.2792	0.4040	0.3201	0.3549	0.3679	0.2705	0.69
Red Brocket deer	0.0247	0.0247	0.0093	0.0432	0.0185	0.0278	0.0340	0.4
Coatimundi	0.3192	0.2394	0.1397	0.1596	0.0599	0.1197	0.2594	0.23
Peccary (collared)	0	0.1076	0.3944	0.1793	0.0717	0.1076	0.0359	0.84
Tegu lizard	0	0.0364	0.0145	0.0291	0.0582	0.0436	0.0364	0.1
Paca	0.0928	0.0190	0.0690	0.0524	0.0571	0.0690	0.0119	0.67
Tapir	0	0.0153	0.0230	0.0096	0.0153	0.0077	0.0096	0.2
Peccary (white lipped)	0.0078	0.0223	0.0223	0.0223	0.0398	0.0214	0.0320	1.25
King vulture	0	0	0	0.0026	0	0.0019	0.0015	0.15
Piping Guan	0.0301	0.0179	0.0124	0.0126	0	0.0144	0.0217	0.15
Howler monkey	0	0.0015	0	0.0010	0	0	0	0.17
Naked-tail armadillo	0	0	0	0.0091	0	0.0016	0.0037	0.39
Agouti	0	0	0.0086	0.0078	0.0031	0.0057	0.0094	1.1
Tinamou	0	0.0109	0.0037	0.0021	0	0.0005	0.0035	0.15
Tayra	0	0	0	0.0026	0	0.0026	0.0028	0.28
Rabbit	0	0	0	0.0036	0	0.0005	0	11.51
Boa constrictor	0	0	0.00169	0.0074	0	0.0032	0	0.1
Crab eating fox	0	0	0	0.0011	0	0	0	0.23
Collared anteater	0	0.0023	0.0017	0	0	0	0	0.48
7-B armadillo	0.00301	0	0.0042	0	0	0	0.0027	0.69
Black vulture	0	0.0032	0.0023	0.0030	0.0032	0.0038	0	0.15
RB toucan	0	0	0	0	0	0.0007	0	0.15

Additional assumptions

The model also consists of a number of parameters that are not based on observations (see submodel explanation below).

Table S8. The key parameters of the model and their default values

parameter	Description	Default values
P_s	Probability hunter goes straight	0.9
W	Weight factor of moving towards camp or continue current direction	0.5
N_A	Number of hunters in a group	5
N_G	Number of groups	3
DC	Days sleep at same camp spot	1 day
R_D	Amount of past decay for comparing expected rate of return	20 days
T_S	Max separate turn	2 degrees
T_A	Max align turn	10 degrees
T_C	Max cohere turn	10 degrees
D_{min}	Minimum distance in flock	0.1 cell
D_{max}	Maximum distance to join cooperative hunt	3 cell
PD	Pursuit decision (Always / Conditional on expected return)	Conditional
ERT	Encounter rate depression (On/Off)	On

Alternative resource distributions

The return rates characterizing each of the seven vegetation types are rather equal in the original landscape. For the alternative resource distribution we amplify the small prey density differences by increasing the encounter rates in the most productive habitat types, and decreasing prey encounter rates in the least productive habitats. Specifically, for the high variation environment we multiplied the prey encounter rates in riparian habitat by 3 and multiplied prey encounter rates in high forest by 2 (Table S9). The remaining 5 vegetation types are multiplied by factors less than one with final prey encounter rates balanced so that the total population of available prey and biomass remains the same over the entire model landscape. For simplicities sake we assume encounter rate directly relates to the population density of species. This is derived by adjusting the multipliers $M_{v,s}$ such that $\sum_v enc_{v,s} \cdot M_{v,s} \cdot ha_v = \sum_v enc_{v,s} \cdot ha_v$, for each species s and where v denotes vegetation type. Encounter rate is defined for each species and vegetation type, $enc_{v,s}$ and the number of hectares of vegetation type is denoted as ha_v . Hence if $M_{v,s}$ is increased for two vegetation types, the others will have to be lower than 1 to meet the condition listed above. The multipliers lead to a more unequal distribution of expected return rates for the different vegetation types (Figure S7), with riparian habitat more than ten times as productive as the meadow habitat.

Table S9. Multiplication of encounter rates for the main species to derived a more unequal distribution of return rates among vegetation types

	Meadow/ grassland	Bamboo forest	Riparian forest	High forest	Low forest	Bamboo understory	Liana forest
Capuchin monkey	0.1	0.1	2.89	2	0.1	0.1	0.1
9-B Armad nest	0.1	0.1	2.59	2	0.1	0.1	0.1
9-B Armad burrow	0.1	0.1	3	2	0.85	0.1	0.1
9-B Armad tracks	0.1	0.1	2.24	2	0.1	0.1	0.1
Red Brocket deer	0.1	0.1	3	1.9	0.1	0.1	0.1
Coatimundi	0.3	0.2	3	2	1	0.2	0.2
Paca	0.1	0.1	2.6	1.8	0.1	0.1	0.1
Peccary (white lipped)	0.2	0.1	3	2	0.35	0.2	0.2

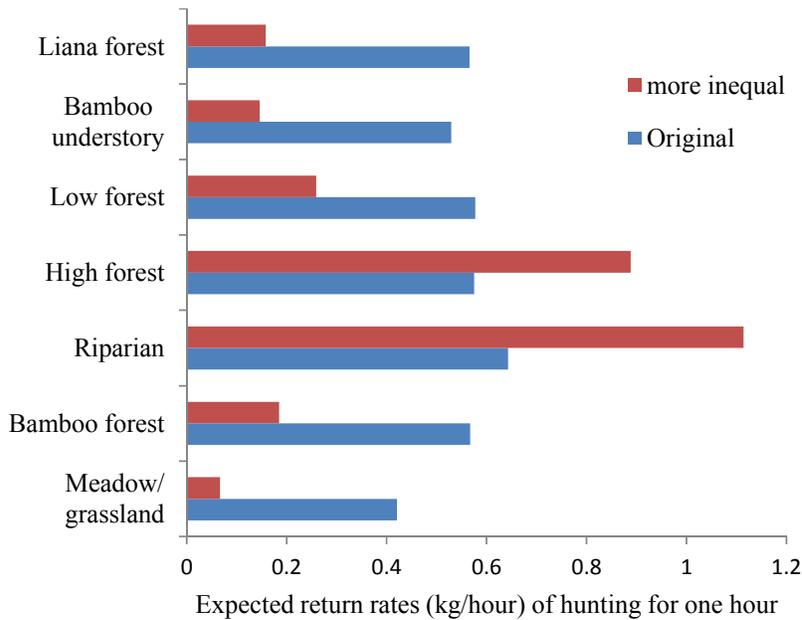


Figure S7: Expected mean return rates on the 7 vegetation types based on prey densities with the original measured values and with the modified encounter rate distribution of higher vegetation variability.

In addition to amplifying the variation of prey densities in habitat types we also modified the landscape by changing the spatial configuration of vegetation types but without changing the total area covered by each habitat type in the model. The natural landscape of the Mbaracayu reserve is composed of multiple habitat types that are distributed in very small patches (often less than 500 meters across). To increase the mean size of habitat patches we take the original

landscape and perturb this by applying an algorithm which checks if randomly swapping the land cover of two cells leads to a higher degree of similarity between directly neighboring cells. We also applied the inverse algorithm make the landscape more fined grained, with extremely small patches of similar habitat. In the original landscape a one hectare cell has on average 60% of the cells with the same vegetation type from the 8 neighboring cells that touch it. In our simulations we created artificial landscapes with 30% and 90% of the neighboring cells containing the same vegetation type. In the analysis we use the same generated 30% and 90% map for all the simulations (given the time consuming way to generate those maps).

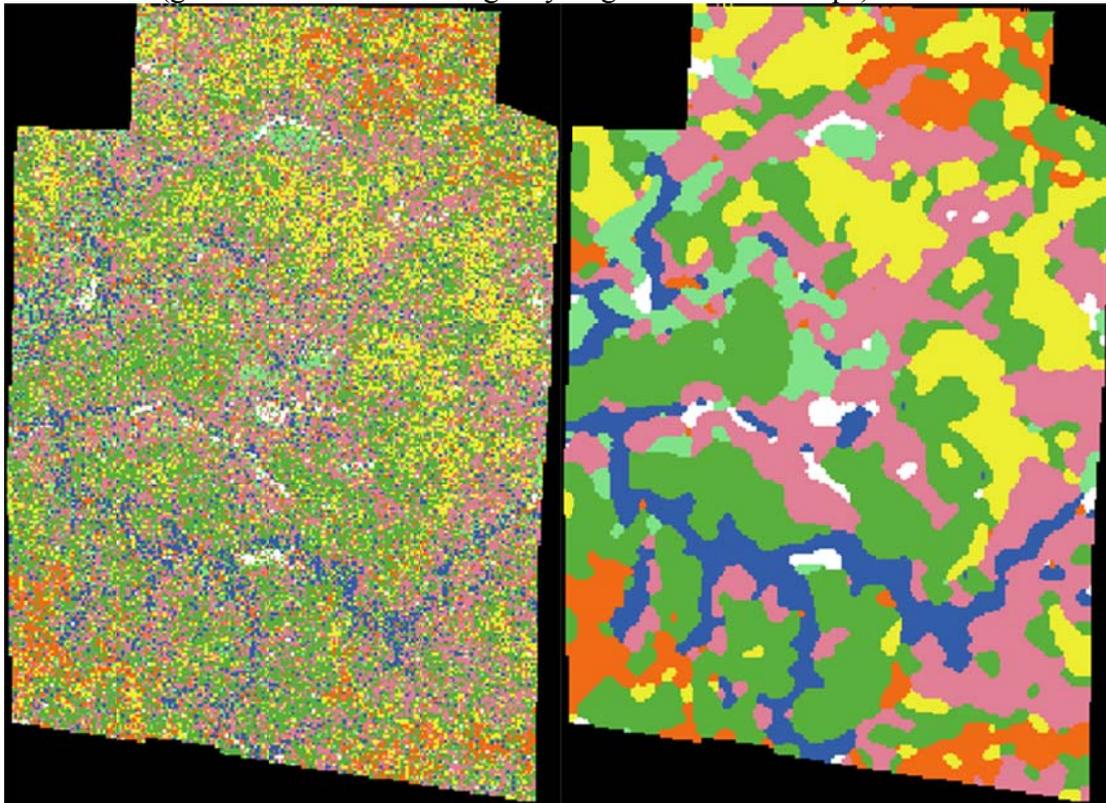


Figure S8. Vegetation maps for less clumped habitat (30), and more clumped habitat (90) conditions compared to the original map (Figure S2).

Submodels

Hereby we discuss various details of the model that direct camp and hunter behavior patterns as well as the operationalization of prey population dynamics.

Camp location

If a camp is moved on a particular day, its new location is placed randomly on the landscape 2 km from the current location. Hunters then move in the general direction of the new campsite throughout the day as specified below.

In this study we include two additional processes to define where to move to and when to move. In the *targeted* campsite version of the model, agents move their camp location into a preferred vegetation type each day. Agents also keep track where each camp has been and do not reuse old campsites for some time period. The targeted condition constrains the new camp location to cells at least 1 km from a recent campsite. When a camp moves, the nearest riparian patch (the vegetation type with the highest return rate) which has not been visited during the last

30 days, is the top priority relocation site. This allows foraging agents to spend more time in the highest return vegetation type in an area that has not been recently depleted. If there is no riparian campsite available meeting these criteria, camp will be located in the next highest return vegetation type (high forest), and so on, as future campsites are prioritized in descending order of expected foraging return rate in the vegetation habitat where they will be located.

When the direction is defined, we will check whether the targeted camp location is between 1 and 3km. If so, the new camp location will be the target. Otherwise, the camp will move 2 km in the direction earlier defined towards the preferred vegetation type.

The original Ache model specified that camp location always moved after a specified number of days (eg. one day). In the new *adaptive* mobility version of the model, the agents residing in a camp together determine whether the average weight of meat hunted over the last few days is above a certain threshold. If so, the camp will remain in its location for another day, if not, the campsite is moved to a new location at the beginning of the day.

These two decision criteria define four broad strategies for a camp: whether it is adaptive or not, and whether certain vegetation type are targeted or not. This leads to a decision tree on how camps are moved through the landscape (Figure S9).

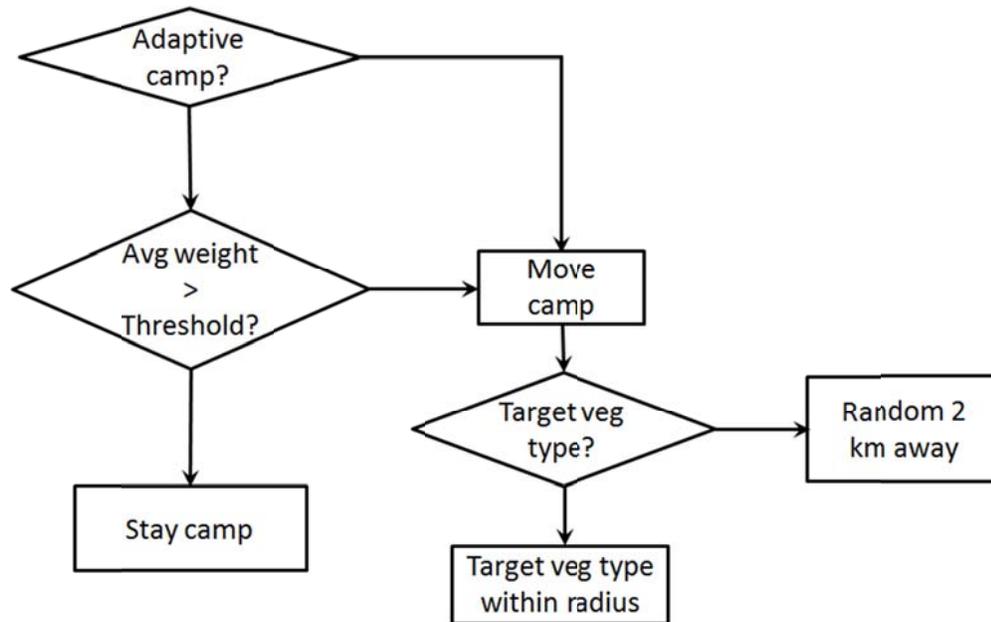


Figure S9: Decision tree for movement of camps including adaptive and targeted movement.

Start of the day

At the start of the day hunters define their initial direction. The initial direction depends on whether hunters are in camps or not, and whether hunters in camps flock or not. If they are not in camps, the hunters draw a random direction from 360 degrees. When hunters are in camps their initial direction is limited from 180 degrees towards the new camp. When hunters flock, the hunters' directions are coordinated and similar.

Movement restriction of agents and camps

When agents move they must remain on the spatial configuration on the model landscape. Before an agent makes a move, we check whether the agent remains in the defined landscape, if not the agent's direction is adjusted a bit and tried again. This process is iterated until a valid move forward can be made.

Flocking

The term "flocking" implies that hunters move in a coordinated fashion. They start in similar directions at the beginning of the day and try to stay together, but not too close. As a consequence hunters adjust their direction every 5 minutes. In ethnographic observation it has been observed that hunters regularly listen to the positions of other hunters and make calls throughout the day to coordinate their movements. If the distance with the nearest hunter is smaller than minimum-allowed-distance, a hunter adjusts his direction to increase the distance using the procedure separate. With a probability (P_S) hunters move straight. But some noise is added, and this noise – changing directions – is larger when an agent is ahead of the rest of the group. This feature of movement slows down the forward motion of agents that are out in front of the rest of the hunting group, so that group pursuits can be achieved. When an agent is walking forward in search of game he must strike a balance between continuing to hunt in his given direction or turning towards the camp. As the elapsed time of a hunting day increases, the program stipulates that an agent is more likely to turn and move towards the camp. The weight of those two direction is determined by:

$\text{degree} = \text{weightfactor} * \text{ticks} / \text{tot-timehunt}$

and as a consequence the heading of the agent is defined as:

$\text{heading} = \text{degree} * \text{campheading} + (1 - \text{degree}) * \text{currentheading}$

Decision to pursuit

An agent decides to pursue an encountered animal if the expected return rate from the pursuit is higher than the average hunting return rate during the last R_D days. The expected return rate is the amount of meat expected to be caught per hour of pursuit time is:

$\text{rt-rate} = (60 * \text{success-rate} * \text{weight}) / \text{minutes pursuit-time}$.

This computed value is compared to the average return rate per hour during the last R_D days. The agents keep track a list of the return rate for each of the last R_D days where the return rate is:

$R_D = (60 * \text{dailyweight}) / \text{minutes time-hunted}$

Time budget

Agents have a time budget for the day of 355 minutes. At the start of the day the budget is defined based on the amount of time used in the previous day compared to the long term average – tot-time-hunt, (355 minutes). When members of a camp use less than 355 minutes on one day, the average time budget for next day goes up, and vice versa. This is formulated as:

time-hunt-budget = time-hunt-budget + (tot-time-hunt- (sum [time-hunted] of agents with [campsite = selfcamp] / nragents))

If the time budget runs out, meaning time to go back to camp is longer than available time on the clock, the agent's direction is towards the camp. However, the agent can still encounter and pursue prey during this time. If a pursuit does take place while returning to camp, the time budget for the next day will be reduced.

In Netlogo this is implemented as

```
ifelse time < (time-hunt-budget - distcamp) [  
  encounterprocedure  
  caldirection  
][  
  if distcamp > 0 [  
    encounterprocedure  
    face camp campsite  
    move  
  ]  
]
```

Cooperative hunting

For a number of prey types, agents can use cooperative hunting techniques during pursuit. When one of these prey is encountered, the agent checks whether there are other agents available within a certain radius. If so, those agents spent a specified number of time units on the cooperative hunt, and continue only afterwards from the location the animal was encountered. To define the group size in Netlogo we calculate:

```
set groupsize count agents with [pursuit = 0 and campsite = campself] in-radius max-distance
```

To calculate the number of animals caught during a hunt, we use the successrate per hunter during a cooperative hunt and draw for each hunter in the cooperative hunt whether an animal is caught or not. The total number of animals caught will be removed from the landscape.

Lizard encounters

Tegu lizards are only active part of the year, namely after day 242. They cannot be encountered during other periods of the year. This matches aspects of their biology whereby they hibernate during much of the year inactive and undetectable.

Encounter suppression

When a hunter has been in a cell during a day there are two possible situations the hunter may encounter a prey type and the harvested individual prey is removed from the landscape, or may not encounter a prey type. In both cases there is encounter rate depression. When hunters pass through a cell or are in a pursuit, they frighten the animals in the cell to hide or move for some time period. This will reduce the probability of encountering a prey. The more hunters pass through a cell the more the encounter rate is depressed. The encounter rate is multiplied by τ_s^{NH} where τ_s is a species specific encounter rate depression parameters (column 4 of Table S4) and

NH are the number of hunters who have recently been in the cell. To define NH we assume that each agent walking through the cell during that day leads to an addition of the value of NH. The next day all cells start with NH equal to zero.

Population dynamics

The encounter rates of prey types in our model are affected by hunting activities. To model the removal of catch, migration and reproduction we developed a simple population dynamic model that applies to each of the cells in the landscape and for each prey species. Our model treats changes in population density and changes of encounter rate (relative encounter rate = RE) as essentially proportional. Hence reproduction, death, migration, etc. affects population density and relative encounter rates equally. At the start of a model run, the relative encounter rate is 1, so that the encounter rates are equal to the measured encounter rate values based on the transect study (Table S2). Over time the value of RE changes.

- Removal of caught prey

When a hunt is successful an animal is caught and this animal must be removed from the landscape. Based on observed animal densities we can calculate the number of cells (nc) on average that are occupied per animal (see Table 7). If an animal is caught the value of RE in that cell and (nc-1) cells nearby are set to 0. To determine the cells which are set to zero we begin by considering the cells adjacent to the cell where prey has been killed starting with a radius of one. We randomly pick cells – if they are within the park – and set RE to zero until nc is reached. If all cells in the radius have been examined and nc is not reached, the radius of possible cells is extended by a distance of one. This process is repeated until nc is reached.

- Migration

Every 3 months there is an update of the relative encounter values by allowing some animals in nearby cells move into “empty” or lower density cells after a conspecific has been harvested. The relative encounter rate for species i and cell j is adjusted as follows:

$$RE_{ij}(t+1) = 0.5 * RE_{ij}(t) + 0.5 (avg_k[RE_{ik}(t)])$$

Where $avg_k[RE_{ik}]$ is the average relative encounter rate of the neighboring cells. This means that migration is not selective but is essentially a diffusion process.

- Reproduction.

Once a year we allow a reproduction event. For simplicity we use a logistic growth function of the relative encounter rates. This relative encounter rate is defined for each species in each cell in the following way,

$$RE(t+1) = RE(t) + r * RE(t) * (1 - RE(t))$$

Where r is the density independent maximum annual growth rate (r_{max}). We assume that the empirically observed encounter rates are a good proxy for the carrying capacity of the species. The calculation of the encounter rate in a particular cell is therefore the observed encounter rate as defined in Table S2 multiplied by the RE of the species in that cell.

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