Non-Lévy Mobility Patterns of Mexican Me'Phaa Peasants Searching for Fuel Wood

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Abstract We measured mobility patterns that describe walking trajectories of individual Me'Phaa peasants searching for and collecting fuel wood in the forests of "La Montaña de Guerrero" in Mexico. These 1-day excursions typically follow a mixed pattern of nearly-constant steps when individuals displace from their homes towards potential collecting sites and a mixed pattern of steps of different lengths when actually searching for fallen wood in the forest. Displacements in the searching phase seem not to be compatible with Lévy flights described by power-laws with optimal scaling exponents. These findings, however, can be interpreted in the light of deterministic searching on heavily degraded landscapes where the interaction of the individuals with their fuel wood-scarce environment produces alternative searching strategies than the expected Lévy flights. These results have important implications for future management and restoration of degraded forests and the improvement of the ecological services they may provide to their inhabitants.

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Introduction

Mobility patterns of humans searching for resources seem to follow specific statistics known to physicists as anomalous diffusion (Klafler and Sokolov 2005). From the prehistoric tribes in Europe searching for quality stone quarrels (Brantingham 2006) to the hunter-gatherers of Africa (Brown *et al.* 2007, 2010), it is becoming clear that distances traversed when humans travel, migrate, disperse and explore a territory is not quite a Gaussian stochastic process but one described by scale-free statistics (Brockmann *et al.* 2006; Flores 2007; Gonzalez *et al.* 2008; Rhee *et al.* 2011).

Understanding the non-Gaussian mobility nature of humans is very important for realistically explaining diverse patterns in humans such as mating (gene flow), cultural changes, foraging, spread of disease and migration processes, all of which have potential and unexpected impacts on

the daily life of individuals and the complexity of societies. Mobility drives the dynamics of encounters among humans and influences the way vital resources and ecosystem services are used, for example food and energy sources. In this study, we measured the patterns of displacements of individual peasants when searching for and collecting fuel wood in the forests of "La Montaña de Guerrero" in the southern Mexican state of Guerrero. We discuss evidence that these patterns do not conform to Lévy flight statistics dominated by power-law probability distributions of the form $P(l) \sim l^{-\mu}$ with scaling exponent μ ($1 < \mu \leq 3$) and l being the length of the displacements. The absence of Lévy flight patterns is not, however, evidence against Lévy foraging as a human mobility phenomenon but rather that, in this case, it is the result of foragers interacting with an environment characterized by the scarcity typical of degraded landscapes.

Conventional optimal foraging theory states that animals and humans search for resources guided by decisions made in order to maximize a given quantity, usually the net energy gain (Charnov 1976; Stephens and Krebs 1986). The efficiency of the search is then in proportion to the behavioral repertoire of the foragers who may employ, to varying degrees, cognitive tools such as memory and information processing when facing the searching space. Most searching models fall in two main groups: (1) random searching where the forager does not have previous information of the prey field such as the spatial distribution or density, and (2) deterministic searching where the forager is able to use memory maps of the territory and therefore has relatively good previous information about the prey field richness and location.

Random Searching

Random searching is by no means exclusively performed by simple low-profile organisms (Hays *et al.* 2011; Matthäus *et al.* 2011), it may be used even by humans under specific environment constraints, for example when searching for a plane that has crashed in the open ocean at an unknown location. It is an optimal strategy when there is no previous information about where the target or prey is located. Recently, optimal random searching theory has been developed further around the so-called Lévy flights (Shlesinger and Klafter 2000; Chechkin *et al.* 2008; Viswanathan *et al.* 2011). It has been demonstrated that step-lengths generated by a power-law probability distribution is an optimal searching strategy when the scaling exponent is $\mu \approx 1$ when the prey is removed (destructive scenario) or $\mu = 2$ when the prey is not removed (non-destructive scenario) (Viswanathan *et al.* 1999).

In the destructive scenario there is no reason to re-visit previous sites such that this searching strategy is conveniently done by "ballistic motion" where successive step-lengths are very large in size and are only separated by a random change of angle. In practice, it corresponds to the strategy of "follow a straight line until you find something". Ballistic searching was first suggested to exist in the very long rectilinear flights of the wandering albatross but was later called into question (Edwards *et al.* 2007, but see also Boyer *et al.* 2008). A non-destructive searching scenario, in which the prey can regenerate or reappear in the same location at a later time, is optimally performed when the forager alternates a few long steps with more abundant short steps. This scenario with $\mu \sim 2$ was found in many biological examples but has also been recently reviewed and questioned citing methodological inadequacies (James *et al.* 2011). Since recent unquestioned examples of Lévy flights are continuously being published (Sims *et al.* 2008; Hays *et al.* 2011), the state of the art of this research area has attracted much interest and is rapidly changing.

Deterministic Searching

Animals and particularly humans may rely on cognitive tools and memory maps in order to perform more efficient searches on a territory previously known or similar to one previously known. A common strategy is "go to the nearest richest place" in which the forager makes a decision on where to go by weighing the profit offered by the site against the energy invested in reaching it, depending on the forager's present location. A well-studied problem related to this deterministic searching mode is the tourist problem in which a tourist wishes to visit a number of cities without repeating them and where some cities are more attractive than others, posing a challenging optimization problem (Lima *et al.* 2001; Stanley and Buldyrev 2001; Campiteli *et al.* 2006). Scale-free movement statistics are known to be an emergent property in models of decision-making intelligent agents performing deterministic searches in heterogeneous environments (Boyer and Larralde 2005; Boyer *et al.* 2009; Boyer and Walsh 2010). Emergent scale-free mobility patterns have been suggested to exist in animals ranging from microzooplankton to spider monkeys, among others (Boyer *et al.* 2004, 2006; Reynolds 2008).

In the case of the spider monkeys' search patterns (Ramos-Fernández *et al.* 2004) it has been suggested that these arise as a consequence of the interaction of the searching individuals with the environment in such a way that characteristics like density and spatial richness distribution influence the searching strategy (Boyer *et al.* 2006). Different searching options may be displayed in different quality habitats. In rich habitats, resources such as food are so abundant at close ranges that long-distance displacements are not expected. At the other extreme, when the

environment is poor with scarce resources, there is no point in traveling far away because the energy invested in long trips is not justified since the gain will be the same as when moving locally. Again long-distance displacements are not expected. The situation is very different when the environment is neither exceptionally rich nor poor. In this case Lévy-like displacement statistics are robustly expected to emerge (Boyer *et al.* 2006, 2009).

Lévy-like statistics have unexpected consequences for social foragers. For example, for spider monkeys it has been shown that complex social structures spontaneously emerge from the interactions of individuals moving under such conditions. These social networkings even have a small-world dynamics (Ramos-Fernández *et al.* 2006). In the case of the Dobe Ju/'hoansi hunter-gatherers' mobility patterns, it was suggested that the Lévy foraging influenced the way tribes visited and remained for a time in specific foraging sites. When individuals from different groups came into contact in these sites, cultural exchanges and intergroup couple mating (gene flow) took place. In this way a complex social structure emerged paired to the local use of resources (Brown *et al.* 2007).

The Me'Phaa of La Montaña de Guerrero

Me'Phaa is a pre-Columbian indigenous ethnic group that inhabits the region known as "La Montaña de Guerrero" (MG) in the state of Guerrero in southwestern Mexico (Martínez 2008). Me'Phaa towns are scattered in the area around the city of Ayutla de los Libres (1654′ N, 9913′ W). The Me'Phaa were until very recently known as "Tlapanecas," which is a pejorative Nahuatl term from the time the Aztec Empire ruled the region. MG is one of the poorest and least developed areas in Mexico, with a Human Development Index (HDI) of around 3.2 (Morales-Hernández 2006; Taniguchi 2011), comparable to some areas of sub-Saharan Africa despite its close proximity to the world-class resort of Acapulco. A typical Me'Phaa individual has no access to health services, schools, paved roads, telecommunications, or electricity, and their situation has been worsened by the recent increase of militarization, social conflict, and violence (Hébert 2006; Camacho 2007).

Fuel Wood Usage and Availability

The landscape of MG is hilly with forest patches mostly on hilltops (Fig. 1). Seasonally tropical dry forest is the most prevalent type of vegetation, but oak and pine forests are present in the highlands (Rzedowski 1996; Pineda-García et al. 2007). The environment is severely degraded with high erosion and deforestation rates (Landa *et al.* 1997). MG is known to have been subject to occupation and anthropogenic impact for as long as 2000 years (Berrìo *et al.* 2006), which has caused the present pattern of degradation. Fuel wood is mostly composed of species belonging to the genera *Acacia*, *Leucaena*, *Lysiloma*, *Prosopis* and *Pithecellobium* (Cervantes *et al.* 1998). *Quercus* and *Pinus* species are also collected when the searching is done in the highlands.

Many Me'Phaa peasants do not have any access to modern energy sources and most continue to rely primarily on fuel wood for low-tech residential uses such as cooking and heating. MG is regarded as one of the main hot spots of fuel
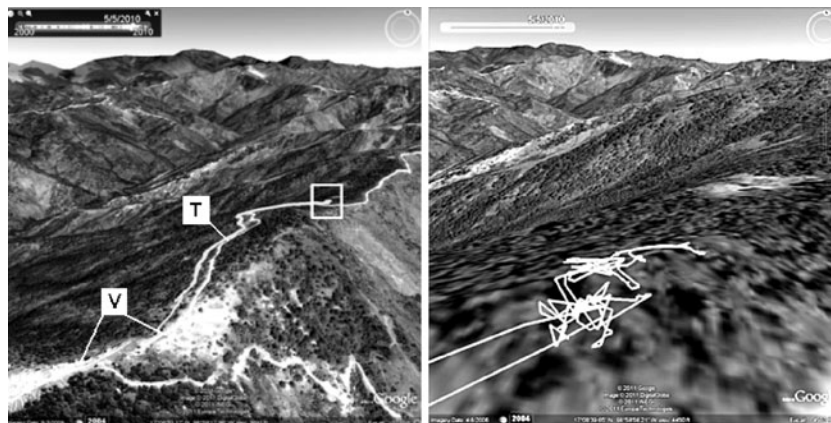

Fig. 1 Panoramic view of the landscape of "La Montaña de Guerrero" in Mexico, one of the poorest regions in the country. The image at the left shows the hilly nature of the seasonally tropical dry forest currently characterized by large rates of deforestation and soil erosion. The image shows one example of a walking trajectory (T) performed by a GPS-equipped peasant when traveling to collect fuel wood. The area of large white spots at the bottom of the image is a village (V) of Me'Phaa peasants of about 20 houses (17.1388969 N, −98.9851532 W, 1,314 msl). At the end of the recorded trajectory there is a shift in the searching behavior that becomes an area-restricted active search. The behavior is shown in the square window that has been enlarged in the image at the right. This last image shows in detail, the actual displacements over the terrain when searching. Images are an overlap of the GPS positions on Google Earth™imagery. Images courtesy of Google Inc

wood usage in Mexico and so requires priority attention since this practice continues to stress the already degraded forest (Ghilardi *et al.* 2007).

Material and Methods

Twelve Me'Phaa peasant volunteers were trained to operate GPS data loggers in order to register positions along a trajectory in the field when searching for fallen fuel wood. The learning process posed no difficulty and after few minutes of manipulating the devices the volunteers showed adequate skill when operating them. Specific instructions were given to switch on the devices when leaving home on a search and collection excursion and to switch them off when returning home. The devices were configured to log data automatically as soon as the first accurate position fix was obtained. The GPS data loggers were worn on a neck lanyard and protected by a plastic bag from dust and rain. All volunteers were males in their 20s to 50s and the searching for fuel wood was done alone with no supervision or accompanied by the research team. Women and children did not volunteer. The peasants were left on their own to carry out the searches whenever and wherever they normally would. Only fallen wood was collected and no trees were felled. Normally, fallen wood is picked up and carried by hand until a sufficient amount is collected and tied together into a bundle carried over the shoulders. All volunteers belonged to an NGO for organic agriculture production based in the city of Ayutla de los Libres (Xuajin Me'Phaa AC). Participants lived in scattered communities in the mountains surrounding the city, separated from each other by several kilometers. The study began in April and finished in October 2010.

We used Holux-M241 data loggers (Holux Technology Inc.) equipped with a MKT GPS-chipset capable of storing 100,000 points. The devices were set to record successive points at intervals of 10 s. This is a reasonable interval since a shorter interval would give measures close to the GPS precision and large intervals could hide the details of the short-range search.

All devices were recovered and the data transferred to a computer for analysis. The data were analyzed with an *ad-hoc* program we developed that implemented a Haversine algorithm to calculate distances between two geo-referenced points on earth. The participants recorded a total of 114 field trips, but only 10 of them contained search-related data. These recordings contained a total aggregated amount of 3,386 displacements, from which 1,231 displacements corresponded to searching displacements with a maximum value of 28.4 m. All displacements less than 1 m were ignored when analyzing the displacements since such distance in 10 s is approximate to a waiting interval. These

values, however, were considered when analyzing the waiting times.

All statistical analysis was conducted using the *R Open Source Statistical Language* (R Development Core Team 2009) on a Linux machine (Ubuntu 11.04). Step-lengths and waiting-times distributions were fitted with two alternative statistical models (Newman 2005; Edwards *et al.* 2007): a power-law $l^{-\mu}$ and the exponential $e^{-\lambda l}$. Maximum Likelihood Estimation (MLE) was used for evaluating model parameters and log-likehood values using the entire time-series. A Model Selection approach involving an Akaike Information Criterion (AIC) was conducted in order to identify which of the two statistical models better explained the data (Burnham and Anderson 2002). The AIC of model i is defined as $AIC_i = -2L_i + 2D_i$, where L is the log-likehood of the fit and D is the number of parameters of the model. The model with minimal value of AIC is regarded as the most parsimonious and is normally considered the most likely to best explain the data (Burnham and Anderson 2002).

Results

The 1-day search and collecting excursions typically follow a mixed pattern of nearly-constant steps when individuals displace from their homes towards the forest (a "ballistic phase") and a pattern of steps with a fat-tail-like distribution when actually doing the searching for fallen wood (Fig. 2). This pattern of mobility behavior is very common in nature and has been given several names (Knoppien and Reddingius 1985; Lomholt *et al.* 2008; Bénichou *et al.* 2011). It is characterized by an adaptive switching between searching behaviors depending on the availability and location of the targets. The first phase is dominated by a simple displacement of the forager to the area of interest and a second phase follows when a potentially resource-rich location is reached. In this second phase, active and careful search behavior is initiated. We ignored the displacements pertaining to the first "ballistic" transportation phase and analyzed only the displacements in the second active search phase.

Step-lengths distribution was fitted with two alternative statistical models using Maximum Likelihood Estimation, a power-law and the exponential. The parameter values found are presented in Table 1 (see Fig. 3). A Model Selection approach points to the exponential model as the most parsimonious, having the lower AIC value. On this basis, we conclude that the Me'Phaa searching displacements are essentially a Brownian-like motion. On the other hand, the waiting times, i.e., the time intervals with no displacements, were analyzed with the same procedure as above (Fig. 4 and Table 1). In this case the lower AIC value suggests that the most likely model explaining the data is the power-law model ($\mu = 2.6$), meaning that the resource is scattered in
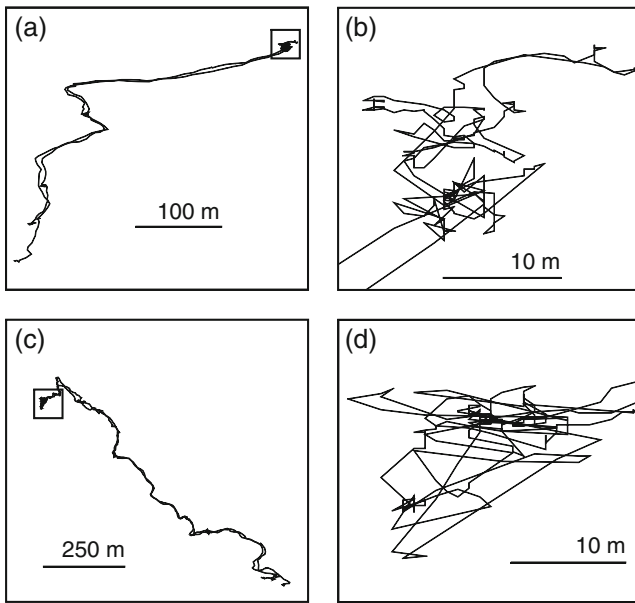
Fig. 2 Two examples of travel and search trajectories as recorded every 10 s by walking Me'Phaa peasants (**a** and **c**). These images show in detail the two phases of the searching and collecting of fuel wood. The first phase is a simple "ballistic" displacement towards the potential collecting site and may span up to several kilometers. When the peasants arrive to the site of interest, the behavior is shifted as shown in the two enlarged figures (**b** and **d**). The pattern of mobility is then replaced by an entangled succession of many short steps and few large steps
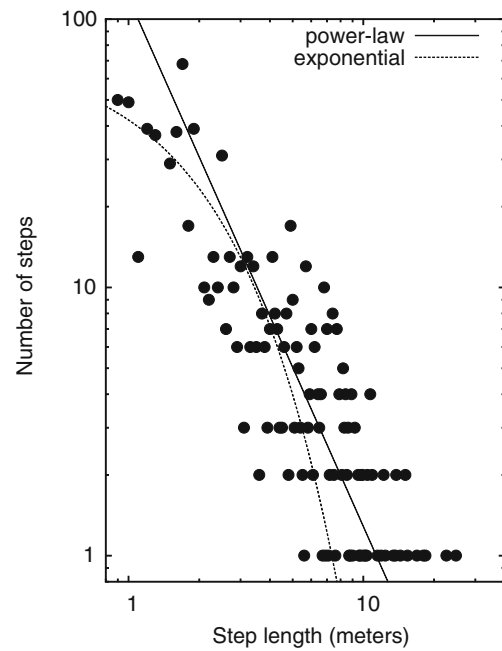

Fig. 3 Statistics of the step lengths. This is a log-log plot of the histogram of the distances traveled by the peasants versus the number of such distances, recorded every 10 s. The straight line shows the power-law fit as estimated using the MLE method. The power-law has a scaling exponent $\mu=1.97$. The curved line is the exponential tested as an alternative model over the same interval (see Table 1). The exponential model better explains the data as suggested by an AIC model selection

patches with amounts of fuel wood following a scale-free probability distribution, a result that is in agreement with the known fact that the size distribution of forest trees and their associated biomass is scale-invariant (Enquist and Niklas 2001).

Discussion and Summary

Mobility is increasingly becoming a problem of interest for anthropology (Brown *et al.* 2007; Richerson and Boyd 2008). Of particular interest is how individual foraging movements influence the pattern of social contacts that in

Table 1 MLE parameter values of two models

Model	Parameter	Loglike	AIC
Step-lengths			
Power-law	$\mu=1.97$	−3336.00	6674.00
Exponential	$\lambda=0.03$	−3274.37	6550.75[a]
Waiting-times			
Power-law	$\mu=2.66$	−162.44	326.89[a]
Exponential	$\lambda=0.47$	−261.01	524.03

[a] This is the lowest AIC value indicating the most parsimonious and likeliest model
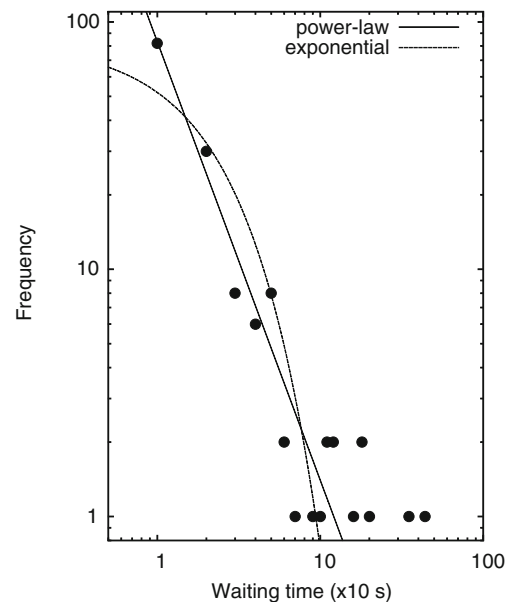

Fig. 4 Statistics of waiting times. This is the log-log plot of the histogram of the waiting times versus their frequency, recorded every 10 s. The straight line shows the power-law fit as estimated using the MLE method. The power-law has an scaling exponent $\mu=2.66$. The curved line is the exponential tested as an alternative model over the same interval (see Table 1). The AIC model selection suggests that the power-law is the most adequate model to explain the data

turn determine the emergence of complex social structures in humans (Brown *et al.* 2007) and non-human primates (Ramos-Fernández *et al.* 2006). The patterns of social contacts are also important for understanding the spatial dynamics of social phenomena such as cultural and social changes (Richerson and Boyd 2008), gene flow (Slatkin 1973; Sokal *et al.* 1989; Wakeley 1999), the spread of diseases and vaccination strategies (Miramontes and Luque 2002; Mao and Bian 2010), among others. Human mobility and the environment are also entangled in a complex matrix of feedback interactions where mobility directly impacts the availability of resources and specific ecosystem services at various scales and where environmental fluctuations and landscape degradation may also negatively influence the patterns of human mobility and social behavior, even enhancing social conflicts (Homer-Dixon 1994; Raleigh and Urdal 2007; Burke *et al.* 2009; Hsiang *et al.* 2011).

For many years, it was thought that human migrations and individual mobility could be described by Gaussian probability distributions; however, recent studies suggest that human mobility may be better explained by anomalous diffusion where the statistics of displacements follow power-law distributions in the form of Lévy flights. The origins of Lévy statistics in human displacement is therefore an issue of increasing interest. Due to the fact that humans search using cognitive tools for decision-making, most of their foraging behavior is aimed at optimizing a cost/benefit ratio, as conventional foraging theory predicts (Charnov 1976). Such optimization is at the core of a modern approach that argues for the existence of a deterministic behavior of searching where the spatial distributions of the target field (richness and density) cause the spontaneous emergence of the Lévy foraging in intelligent agents (Santos *et al.* 2007; Boyer 2008; Boyer *et al.* 2009). When the environment is scarce in resources, deterministic searching force non-Lévy patterns of displacements because the Lévy stable distributions start converging into a Gaussian one when the scaling exponent μ of the power law is >3 (Chechkin *et al.* 2008; Nurzaman *et al.* 2011). Such non-Lévy patterns are the best local strategy for such environments but these are non-global optimal solutions.

It is estimated that nearly 2.5 billion people in developing countries world-wide make use of fuel wood in order to meet their residential energy needs (IEA 2009). Most of these people live in areas subject to strong environmental pressures. This is the case for the Mexican Me'Phaa peasants in "La Montaña de Guerrero" in Mexico. This impoverished indigenous group has inhabited the area since pre-Columbian times and so have exploited the ecosystem since then with non-renewable large-scale management strategies. We studied the mobility patterns of the Me'Phaa peasants when searching and collecting fuel wood in the field. We found a mixture of foraging behaviors that consist

of a long trip (up to several kilometers on foot) from their homes to the collecting sites. This phase is composed of nearly constant distance steps that mostly follow the path of roads or tracks and is similar to a "ballistic behavior" where there is no active searching at all. When arriving to an interesting site that contains a significant amount of fuel wood, the movement behavior is replaced by an active search composed of a mixture of abundant small steps alternated with few long steps in a fashion reminiscent of intermittent searching (Knoppien and Reddingius 1985; Lomholt *et al.* 2008; Bénichou *et al.* 2011). The statistical distribution of the step lengths is better explained by an exponential model.

What is the meaning and the origin of an apparently non-optimal Brownian-like movement pattern in the Me'Phaa searching process? First we should examine in more detail the searching behavior of the individuals. When arriving in the area to be searched, peasants do have a fairly good view of where the fallen wood lies around since the density of trees is low in a degraded seasonally tropical dry forest (also, there are no other major physical obstacles). This means that the individuals would not move around searching randomly as if blind. Instead, they will move to where they see (tens of meters) there is fallen wood of good size and in good quantity. This searching behavior is then repeated and it matches the pattern of a deterministic search as explained in the introduction. We rule out the behavior leading to a Lévy distribution with optimal scaling exponents $\mu=1$ or $\mu=2$, typical of random searching scenarios (Viswanathan *et al.* 2011). Instead we emphasize that in models of deterministic searching it has already been argued that environments with scarce resources may lead to Brownian-like displacements. This does not mean that the search is inefficient but that a Brownian-like searching pattern becomes locally optimal under such extreme conditions (Boyer *et al.* 2006, 2009).

Brownian-like behavior is also known to occur in other primates (Schreier and Grove 2010; Sueur 2011), stressing the importance of considering the role of the environment in influencing the mobility patterns of foragers. Spatial distribution, density, and resource abundance cannot be separated from the study of forager mobility (Miramontes et al. 2012; de Jager *et al.* 2011), especially since they impact decision-making and optimization efforts (Boyer *et al.* 2009).

Fuel wood search and collection by Mexican Me'Phaa peasants are characterized by large amounts of energy invested in traversing large distances on foot for poor profit, since the collection is limited by the carrying capacity of the individuals. Therefore the searching behavior of the Me'Phaa, despite involving elaborate decision-making and complex interactions with the environment, is far from a global optimal solution. This situation could be reversed or improved if Me'Phaa peasants were encouraged and

assisted in actively engaging in the adoption of forest restoration practices that would increase the availability of wood close to their homes, reversing a trend of failures of previous attempts to reforest this region (Cervantes et al. 1996). Research on the restoration of ecosystem services in the region through agroforestry practices is currently in progress as follow-up to the research presented here.

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