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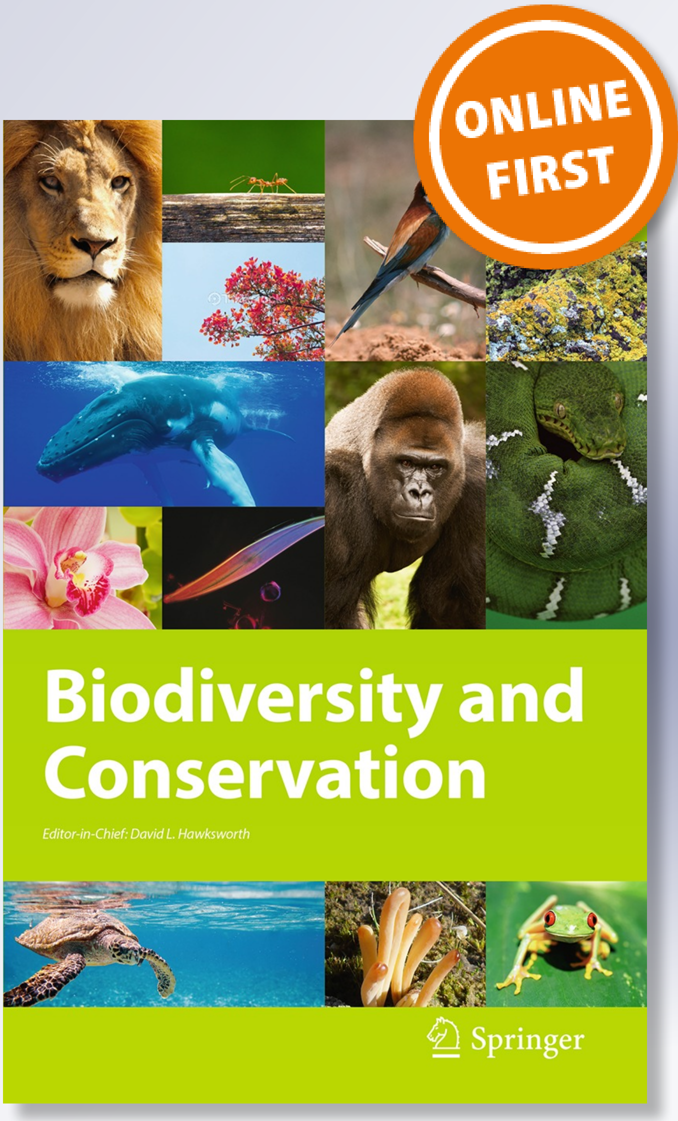

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Towards a traditional ecological knowledge-based monitoring scheme: a proposal for the case of edible mushrooms

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Abstract Monitoring wild edible fungi over long periods is essential to understand how environmental or cultural factors influence fruiting patterns. Since conventional sampling methods are time and resource intensive, alternatives providing reliable ecological information could be useful for assessments of fungal management. Traditional ecological knowledge (TEK) can be used as a sampling alternative in a cost-effective manner. Thus, in this paper we aim to: (1) illustrate how GPS-recorded information on mushroom gatherers' pathways can be used to describe fungal diversity and distribution patterns, and (2) outline a TEK-monitoring proposal that can provide communities and researchers with high-quality ecological data on edible mushrooms. Using information from 32 trips (55 GPS-tracked pathways) we were able to describe the frequency, abundance, diversity and spatial distribution of edible fungi at different sites. We recorded the collection of 6,905 sporocarps, representing 20 species and 6 genera, which were collected or identified at

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2,683 locations. In addition to *collections*, we suggest consistent recording of fungal encounters defined as *memory*, *exploration*, *traces*, and *failed collection*, as these also provide ecological information. The most gathered species, *Turbinellus floccosus* and *Clitocybe gibba*, were also among the mushrooms most frequently listed by local people. Finally, we propose combining our GPS-tracking method with a thorough TEK investigation and participatory research in order to develop adaptive co-management strategies that allow local people to manage and conserve their forests through the integration of traditional and scientific knowledge.

Keywords GPS-tracking · Local knowledge · Participatory research · Conservation · La Malinche National Park

Introduction

The exploitation of natural resources in order to meet the increasing nutritional and energy demands of a rapidly growing human population is threatening the biodiversity of ecosystems around the world. Tropical forests, for example, were the primary sources of new agricultural land from 1980–2000 (Gibbs et al. 2010), and Sarukhán et al. (2009) have reported that by 2002 Mexico's vegetation had been reduced to 38 % of its original area. Importantly, human expansion across forested areas is occurring at a higher rate than efforts to recover biodiversity loss. As one means of confronting this impending crisis, scientists have been studying and documenting traditional practices and knowledge that allow different ethnic groups to sustainably use and manage their environment (Diemont and Martin 2009; Toledo et al. 2003). Habitat loss and economic factors increasingly result in young people migrating from rural areas to urban centers, where they engage in activities that no longer have any relation to the forest management practices that form part of their community's Traditional ecological knowledge (TEK). TEK is defined by Berkes et al. (2000) "as a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment". After studying human communities in arid environments of Patagonia, Ladio and Lozada (2009) suggested that extreme changes in both social and ecological scenarios can be buffered by diversifying economic activities and restoring ancestral practices of sustenance. An evaluation of Local ecological knowledge (LEK)[1] reliability by Anadon et al. (2009), who studied the tortoise *Testudo graeca* in Southeastern Spain, revealed that interviews with shepherds yielded abundance estimates in a much wider range than linear transects. Local inhabitants' ecological knowledge derives from their interaction with landscapes on large scales and over longer time spans than are possible in scientific investigations (Uprety et al. 2012). We therefore consider it necessary to explore alternatives that permit indigenous people and scientists to systematically record the traditional use and availability of forest resources.

Given their potential as a source of food and income for rural families, in this report we focus on the example of edible mushrooms. As a taxonomic group, fungi fulfill a wide

[1] People's knowledge of abundance and distribution of species usually gained from individual's observations. In this paper we will use TEK and LEK as synonyms, even when the latter is not handed down through the generations.

variety of functions in ecosystems (parasitic, saprobic, symbiotic, mutualistic or food source). For this reason their study, management and conservation play a central role in the sustainability and quality of human life (O'Dell et al. 1996; Swift 2005). The fungal groups that people commonly take from forests are those with large sporocarps (mushrooms, truffles, puffballs, shelf, and cup fungi), many of which live on fallen wood or in association with the roots of particular tree species. The latter, known as mycorrhizas, generally constitute mutualistic or obligatory relations for the growth and survival of the organisms involved (Baxter and Dighton 2005; Mueller et al. 2006) and their presence is thus closely associated with the health of the ecosystem. Yet, "fruit-body production of mushrooms is not well understood to date, as many factors interact with mushroom growth in nature" (Egli 2011). Studies carried out in European forest communities (Arnolds 1991; Egli 2011) found that fewer ectomycorrhizal fungi were producing sporocarps since the 1950′s, and suggested different causes for such a decline (e.g. habitat loss, air pollutants, soil acidification, nitrogen deposition, litter accumulation, and reduced tree vitality).

Conventional methods designed to study fungal biodiversity or ecology often require several years (Hawksworth 2003) to avoid sampling only common and prominent species and missing rarer or inconspicuous taxa (Cannon 1997; Gordon and Newton 2006). However, funding specialists to systematically monitor and taxonomically identify fungi in the field for prolonged periods can be expensive, although with the advantage that results from different regions can be compared (Balice et al. 1997). Moreover, to date there is still no sampling method to study macroscopic fungal communities that is accepted universally (Hawksworth and Mueller 2005; Rossman et al. 1998). Thus, indigenous peoples' knowledge and perceptions have also been used by scientists in order to rapidly assess trends in biodiversity within an area (Hellier et al. 1999), or to construct maps of communities' resources and territories (Smith 2003; Smith et al. 2003). In fact, local or traditional knowledge has been "increasingly used by ecologists to address diverse questions that often focus on applied conservation issues and may incorporate local knowledge with biological data from more conventional research and monitoring" (Brook and McLachlan 2008).

TEK in relation to fungal biology, ecology, phenology and usage in Nahua, Otomi and Mestizo communities within La Malinche National Park (LMNP) in Central Mexico has been described by Montoya et al. (2002, 2003). Most people associated mushroom availability with wild (not cultivated) forest, and mushroom growth (fructification) with the rainy season. Montoya et al. (2004) have reported up to 93 mushroom species in LNMP, all recognized by local people using their indigenous or Spanish names, and their different uses (e.g. food, cosmetics, insecticides, medicine, ornaments, or trade items) (Montoya et al. 2002).

Mushroom gathering trips carried out by members of indigenous communities in LMNP provide a good opportunity for exploring the utility of a GPS-tracking method to monitor edible mushroom availability in *Abies* and *Pinus*-*Quercus* forests. As a result of previous experience and continuous exploration of their environment, fungi gatherers develop an expertise for determining where and when to search for edible mushroom species. Pacheco-Cobos et al. (2009) confirmed this while GPS-tracking gatherers who were often aware of the presence of edible species even in the absence of fruiting bodies. The GPS-tracking method developed by Pacheco-Cobos et al. (2009, 2010) can provide: (i) a considerable amount of information in a short time; (ii) preliminary assessments of fungal diversity (and distribution) that would allow scientists to conduct initial site evaluations; and (iii) a systematic sampling protocol allowing proper comparisons between sites. These features were recognized by Cannon (1997) as desirable in order to rapidly assess and study fungal diversity worldwide. We suggest that GPS-tracking and TEK-investigation could complement conventional sampling methods for monitoring forest resources, and provide local users and scientists with relevant ecological information for the development and improvement of plans to conserve and manage ecosystems (Etkin et al. 2011; Pilz and Molina 1996).

Thus, our aims in this paper are to use collection records of edible fungi and field experiences obtained while GPS-tracking mushroom gatherers in LMNP (Pacheco-Cobos 2010): (1) to illustrate how these data can be used to estimate fungal diversity according to Cannon's (1997) suggestions (i–iii) listed above, and (2) to outline an integrated TEK-based monitoring approach which local gatherers and scientists can use to systematically monitor forest resources.

Methods

Study area

LMNP covers an area of 45,852 ha, located between the central Mexican states of Tlaxcala and Puebla (19°06′ and 19°20′N, 97°55′ and 98°10′W) and has a peak altitude of 4,461 m asl. According to Olson et al. (2001) most of the volcano lies within the *Tropical and Subtropical Coniferous Forests*, more specifically within the *Trans-Mexican Volcanic Belt* ecoregion for which annual precipitation is 970 mm. A part of LMNP's Northeast corner lies within a *Deserts and Xeric Shrublands* biome, in the *Tehuacan Valley Matorral* ecoregion (Olson et al. 2001) where annual precipitation is 648 mm. Temperature and vegetation types vary along an altitudinal gradient (Villers-Ruiz et al. 2006): 12–18 °C with *Quercus* and *Pinus* communities below 3,000 m asl, 5–12 °C with *Pinus*, *Alnus* and *Abies* communities above 3,000 m asl, and 2–5 °C with grassland communities and *Juniperus monticola* above 4,000 m asl.

Tracking and site selection

We GPS-tracked mushroom gatherers (Pacheco-Cobos 2010; Pacheco-Cobos et al. 2010) from San Isidro Buensuceso, Tlaxcala, during three consecutive rainy seasons (2005–2007), while searching for fungi in eight different locations within LMNP. On each trip (N = 32) one or two simultaneous pathways were recorded (Table 1). All subjects followed were contacted in advance and gave their informed consent to be tracked.

Table 1 Number of trips and GPS-tracked pathways in LMNP

Site	Trips	Pathways	Year
1	7	11	2005–2007
2	4	6	2006, 2007
3	1	1	2007
4	7	13	2005–2007
5	6	11	2005–2007
6	2	4	2006
7	4	8	2006, 2007
8	1	1	2005

Mushroom gatherers chose the locations to be visited within LMNP according to their estimates of fungi return rates.

Sampling and analysis

Our dataset is composed of 55 pathways containing the date, site, sequential pairs of geographical coordinates, species' traditional names (for verification see below), and number of sporocarps for each fungal encounter. Five types of fungal encounters were identified, but not all were consistently recorded: (1) *memory*, cases in which gatherers remembered and signaled places where they had previously collected mushrooms; (2) *exploration*, cases in which gatherers inspected areas where fungal presence was suspected; (3) *traces*, cases in which rotten fungal sporocarps, those eaten by local fauna, or traces of collected sporocarps were found; (4) *failed collection*, cases in which sporocarps were not collected after being closely inspected and recognized as not edible by gatherers; (5) *collection*, 2,406 cases in which fungal encounters resulted in gathering. Only type 5 encounters were consistently recorded. In some cases registered encounter types could not be associated with any particular fungal species because gatherers were moving quickly and did not reply to researchers' inquiries. Such *no-species-registered* encounters still constitute part of the search and represent locations where sporocarps could be collected later.

The traditional names of mushrooms encountered by gatherers were matched with their corresponding scientific names using the lists reported by Montoya et al. who collected fruiting body samples located along the transects of eight sampling units (2014) or along paths walked while following key informants (2003). All Montoya et al.'s samples were processed as voucher specimens for identification, and deposited at the Tlaxcala herbarium (TLXM).

We used R Core Team (2014) packages *sp* (Bivand et al. 2013; Pebesma and Bivand 2005), *rgdal* (Bivand et al. 2014), and *spatstat* (Baddeley and Turner 2005) for analyzing data. To describe the typical mushroom gatherer's sample day we calculated the mean and standard deviation values (N = 55) for the following parameters: distance traveled (km), trip duration (hours), number of collection events, number of sporocarps, number of species or genera gathered, and total fresh weight of all sprorcarps.

To analyze the diversity of edible fungi we considered each site visited as a single sampling unit, and each GPS-tracked pathway as a separate transect. For each site, we calculated: (1) *frequency* as the number of collection events per species or genus, (2) *relative frequency* as the number of collection events per species divided by the total number of collection events for all spp, (3) *abundance* as the number of sporocarps collected per species, and (4) *relative abundance* as the number of sporocarps for each species divided by the total number of sporocarps for all spp. We described sites in terms of their total species or genus *richness* (cumulative number of species based on a series of samples) and *diversity*. For the latter we calculated and compared the *Shannon's* index (Shannon 1948; Zak and Willig 2004) ($H' = -\Sigma\, p_i \ln p_i$, where p_i represents the relative frequency or the relative abundance of the ith species, and ln is the base e log), and the *McIntosh's* index (McIntosh 1967) ($U = \sqrt{\Sigma\, n_i^2}$, where n_i represents the number of collection events or sporocarps of the ith species). We also estimated *McIntosh's* index as a percentage of the theoretical maximum possible for a given number of species, $D = (N-U)/(N-\sqrt{N})$, where N is the total number of collection events or sporocarps. All parameters were estimated for the whole sampling period.

Geographical coordinates for each collection event and species were used to calculate the *Clark-Evans* index (Clark and Evans 1954). Geographical coordinates were normalized by subtracting the minimum and dividing by the range (Jajuga and Walesiak 2000), according to the general formula: $x' = x - \min(x)/\max(x) - \min(x)$. Based on the distance from each coordinate pair to its nearest neighbor, such an index can define species' spatial distribution type (random, uniform, or clumped). We selected sites visited at least four times for calculating the most gathered species' *Clark-Evans* mean index. Given that this index can be used for two dimensions only, we analyzed elevation separately. Statistical analyses and significance values were not calculated as our sampling design, originally intended to balance the sex of the mushroom gatherers (Pacheco-Cobos et al. 2010), did not balance the number of visits to sites or the number of pathways tracked.

Results

An average mushroom gatherer, walking through the forest for about 4 h, collected around 126 sporocarps of different species at 49 different locations. Table 2 summarizes the statistics for a mushroom gatherer's average day.

From 55 GPS-tracked pathways, a total of 6,905 sporocarps were collected or recognized at 2,683 locations. At 277 of these locations a fungi species was identified, although no sporocarp collection took place. The number of encounter types associated with unsuccessful collection records, were: 14 for *memory*, 45 for *exploration*, 17 for *traces*, and 258 for *failed collection*. There were 57 additional locations for which no species could be registered although the presence of mycelia of edible fungi was presumed.

A total of 20 species and 6 genera were identified from their traditional names (Table 3). Only in one case were we unable to match the mushroom's traditional name with the scientific one, because it was not listed by Montoya et al. (2003, 2004) and we did not sample or photograph it.

Diversity and distribution

Increasing the number of tracked pathways per visit helped in registering most of the collected edible fungi richness, and thereby allowed reliable comparisons between sites. Species richness varied slightly from 19 to 23 at the most visited sites (1, 2, 4, 5, and 7), and dropped to values between 4 and 6 at the least visited sites (3 and 8). For site 6, where four pathways were GPS-tracked on two visits, species registered rose to 16.

With regard to frequency (see Online Resource 1, Table S1, for values obtained at each site), we found that *Turbinellus floccosus* and *Clitocybe gibba* were the most common

Table 2 Values for a typical mushroom gathering trip

Descriptor	Mean ± SD	Range
Distance (km)	7.4 ± 2.4	3.7–15.8
Time (hours)	3.9 ± 1	2.1–6.2
Collection events	49 ± 32	7–155
Sporocarps	126 ± 89	3–403
Spp (or Genus)	8 ± 3	1–14
Fresh weight (kg)	3.7 ± 2.9	0.1–15

Table 3 Collected (edible) species identified by their common names

Nahuatl	Spanish	Species or genus[a]
Ayoxochitl	Flor de calabaza, yemita	*Amanita bassi* Guzmán & Ram.-Guill.[M]
	Bate	Not identified
	Cailita, micailita, canelita	*Tricholoma equestre* (L.) P. Kumm[M]
Chilnanacatl	Enchilada, hongo de chile	*Lactarius salmonicolor* R. Heim & Leclair[M]
Cuatecax, tecax	Trompa de cochino	*Russula* spp.[M]
Gachupi	Charrito blanco	*Helvella crispa* (Scop.) Fr.[M]
Gachupi	Charrito blanco o negro	*Helvella* spp.[M]
Gachupi, cuatlil	Charrito negro	*Helvella lacunosa* Afzel.[M]
Huexonanacatl	Hongo de maguey	*Pleurotus opuntiae* (Durieu & Lév.) Sacc[S]
Izquilo	Oreja de ratón	*Clitocybe gibba* (Pers.) P. Kumm[S]
	Mantecada	*Amanita rubescens* Pers.[M]
Ocoxal	Coyotito	*Hebeloma mesophaeum* (Pers.) Quél.[M]
Olonanacatl, olote	Mazorca	*Morchella* spp.[M, P]
Poposo	Panza	*Suillus pseudobrevipes* A.H. Sm. & Thiers[M]
Tecosa	Tecosa – amarillo	*Cantharellus cibarius* Fr.[M]
Tlapalxotoma	Pante rosa	*Boletus atkinsonii* Peck[M]
Tlapitzal	Corneta	*Turbinellus floccosus* (Schwein.) Earle ex Giachini & Castellano[M]
Tlapaltecosa	Tecosa – morado	*Chroogomphus jamaicensis* (Murrill) O.K. Mill.[M]
Totoltenanacatl		*Agaricus augustus* Fr.[S]
Totomoch		*Clitocybe* spp.[S]
Xelhuas	Escobeta - amarilla, de durazno, de rosa, de encino, café, morada	*Ramaria* spp.[M]
Xilona	Señorita, güerita, blanquita, poblanita	*Hygrophorus chrysodon* (Batsch) Fr.[M]
Xiteburo, cefamile	Hongo de casquillo, huevito	*Lycoperdon perlatum* Pers.[S]
Xocoyoli, xoxocoyoli		*Laccaria trichodermophora* G.M. Muell.[M]
Xoletl, xoletes	Hongo blanco	*Lyophyllum decastes* (Fr.) Singer[S]
Xotoma, xotoma blanco	Pante, panza, pancita, pata de elefante, pata gorda, pante güero	*Boletus* spp.[M]
Xotlalix, tetecuitl		*Armillaria* aff. *mellea* (Vahl) Mesch.[P]

[a] Ecological value: *M* mycorrhizal, *S* saprobic, *P* parasitic

species at all sites, with a total of 736 and 694 collection events, respectively. They were followed by *Ramaria* spp. and *Lactarius salmonicolor* with 277 and 244 collection events respectively, and then by *Boletus* spp., *Laccaria trichodermophora*, and *Hygrophorus chrysodon* with total collection events ranging from 129 to 98. The total number of collection events for the remaining species varied between 47 and 1.

Table 4 Richness and diversity of fungi species at visited sites

Site	Position	Richness	Shannon		McIntosh			
			H'_{freq}	H'_{abun}	U_{freq}	U_{abun}	D_{freq}	D_{abun}
1	East	23	2	1.6	287.2	820.4	0.6	0.5
2	West	20	2.5	2.2	50.9	166.5	0.7	0.6
3	North	4	1	0.5	11.4	32.2	0.4	0.2
4	Northeast	20	2.2	1.7	264.3	835	0.6	0.5
5	West	21	2.4	2	171.4	489.4	0.7	0.6
6	Southwest	16	2.3	2.1	41.4	116.8	0.7	0.6
7	Northwest	19	1.9	1.6	327.6	1009.9	0.5	0.5
8	East	6	0.9	0.7	26.3	42.2	0.3	0.2

The perspective offered above was modified when species' abundance was considered (see Online Resource 1, Table S2, for values obtained at each site). *T. floccosus* and *C. gibba* were still the most abundant species, with a total of 2,429 and 2,066 sporocarps, respectively. The next most abundant group of species was formed by *L. salmonicolor*, *Ramaria* spp., *H. chrysodon*, *L. trichodermophora,* with a total abundance of sporocarps ranging from 404 to 294. These were followed by *Boletus* spp., *Lyophyllum decastes*, *Hebeloma mesophaeum*, and *Clitocybe* spp., with abundance values between 123 and 107. The remaining species' abundance values ranged from 96 to 1.

The mean number of sporocarps gathered per encounter, calculated for the most consistently collected species at the most visited sites, was (rounded values): four for *H. chrysodon*; three for *C. gibba*, *T. floccosus*, and *L. trichodermophora*; and one for *L. salmonicolor*, *Ramaria* spp., and *Boletus* spp.

According to *Shannon's* and *McIntosh's indices*, of the sites considered in the analysis, site 2 was the most diverse, independently of using p_i or n_i as frequency or abundance values (Table 4), and site 7 was the least diverse. According to *McIntosh's* index *D*: sites 2 and 5 were the most diverse irrespective of whether frequency or abundance values were used as n_i, site 7 was the least diverse when n_i corresponded to frequency, and sites 1, 4 and 7 were the least diverse when n_i corresponded to abundance (Table 4). Sites 3, 6 and 8 were not considered for this rough comparison since trips to these sites were infrequent.

The *Clark-Evans* index values indicated that *Amanita rubescens* and *L. decastes* were evenly distributed, whereas the remaining species presented a clumped distribution (Table 5). We also found that the altitude values recorded for most species were between 3,000 m and 3,600 m. Only the altitudes for *Agaricus augustus*, *Boletus atkinsonii,* and *Armillaria aff. mellea* were below this range and showed, together with *Chroogomphus jamaicensis*, wide altitudinal ranges (Fig. 1).

Discussion

Usefulness of GPS-recorded data

Data obtained from GPS-tracked pathways of mushroom gatherers proved to be useful for describing fungal diversity (frequency and abundance) and distribution patterns at repeatedly visited sites within LMNP. With only 32 trips to the forest we were able to

Table 5 *Clark-Evans* index mean for each species at most visited sites

Species or genus	Clark-Evans	SD
Amanita basii	0.36	0.11
Tricholoma equestre	0.60	0.20
Lactarius salmonicolor	0.57	0.44
Russula spp.	0.52	0.20
Helvella crispa	0.23	0.20
Helvella spp.	0.51	0.28
Helvella lacunosa	0.86	0.51
Pleurotus opuntiae	NA	NA
Clitocybe gibba	0.41	0.09
Amanita rubescens	1.11	0.51
Hebeloma mesophaeum	0.53	0.37
Morchella spp.	0.59	0.38
Suillus pseudobrevipes	0.61	0.18
Cantharellus cibarius	0.26	0.18
Boletus atkinsonii	0.06	NA
Turbinellus floccosus	0.35	0.11
Chroogomphus jamaicensis	NA	NA
Agaricus augustus	NA	NA
Clitocybe spp.	0.48	0.03
Ramaria spp.	0.46	0.14
Hygrophorus chrysodon	0.38	0.24
Lycoperdon perlatum	0.71	0.27
Laccaria trichodermophora	0.63	0.25
Lyophyllum decastes	1.09	0.29
Boletus spp.	0.57	0.19
Armillaria aff. *mellea*	NA	NA

collect a considerable amount of information on the availability of edible fungi. These results, however, are not intended for comparison with those obtained by conventional sampling methods. Nevertheless, satellite technologies have become a key tool in ecological studies, and by using "…GPS, collectors can map populations and individuals to document spatial patterns of harvest both within populations and across landscapes." (Etkin et al. 2011).

Our GPS-tracking method fulfills three (numbered i–iii above) of Cannon's (1997) recommendations for achieving a rapid assessment of fungal diversity, and can be used worldwide. By following and GPS-tracking mushroom gatherers we were able to record information from a wider range of geographical areas or slopes (Table 4) than the ecological survey by Montoya et al. (2014). This is consistent with other findings, where local knowledge is recognized to estimate abundance across a much wider range than linear transects (Anadon et al. 2009; Fraser et al. 2006). Preliminary assessments of fungal diversity could help explore differences in the diversity of edible fungi between or across sites on local or global scales. Given that most of the species gathered are mycorrhizal (Table 3) and that fungi are seldom legally protected (Manoharachary et al. 2005), monitoring their availability in the forest is a key prerequisite for understanding their fruiting patterns and applying acquired knowledge to develop conservation strategies.

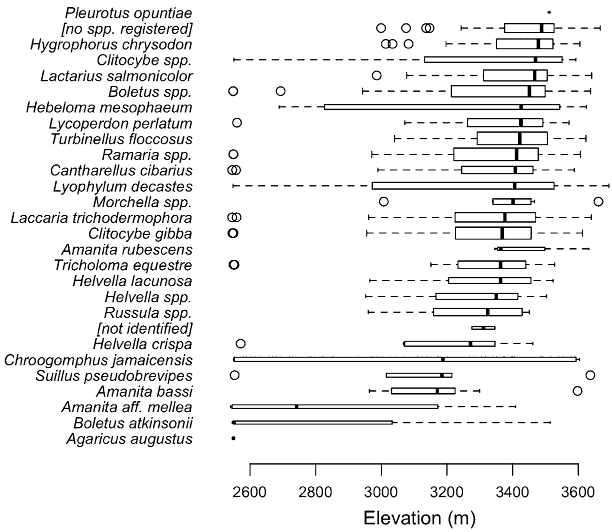

Fig. 1 Altitude distribution ranges of species in our dataset. The width of each box is proportional to the square-root of the number of observations for each species; *horizontal bars* within boxes give medians, *horizontal limits* to the boxes represent the 1st and 3rd quartiles, *broken vertical lines* display the range, and *circles* represent outliers

This method might help assess environmental or anthropogenic influences on edible fungi availability. In relation to this, Montoya et al. (2014) mention that the lower diversity ($H' = 1.78$) observed on the Southeast slope of LMNP, could be related to the higher commercialization of fungi collected by people of neighboring communities. Our estimated H' for a neighboring area, site 1 ($H'_{abun} = 1.6$, Table 4) was similar to the estimates of Montoya et al. (2014). We found our H' and U values to be consistent in describing the diversity[2] at the sites, although values for D were coarser; e.g. whereas H' and U reported only site 2 as the most biodiverse, D reported sites 2 and 5 to be the most diverse (Table 4). Such similarities and discrepancies are expected according to Magurran (1988) and Zak and Willig (2004), who state that indices H' and U have a better ability to discriminate diversity among sites than index D.

Cultural preferences should be further studied in order to learn how collection intensity affects mushroom production. For example, at most of the sites visited we observed that the most frequent and abundant species, *T. floccosus* and *C. gibba*, were the first and ninth (of 52 names of fungi) most frequently mentioned in a free listing by villagers of our study population of San Isidro Buensuceso (Montoya et al. 2003, p. 803). Also, local idiosyncrasies should be taken into account in order to: (i) adjust the tracking method for handling cases where species' common names overlap (i.e. *Helvella crispa* or *Helvella lacunosa*), (ii) identify rare species such as the unidentified one in the present study, and (iii) investigate cultural reasons for not collecting species that are known to be edible (i.e. *Amanita rubescens*).

Our ecological and spatial data should be interpreted cautiously due to the sampling bias given by the foragers' preferences for certain fungi and collection sites. Nevertheless, the

[2] Sorting *H'* values in descending order, and *U* values in ascending order. Note that higher *U* values are associated with lower richness (McIntosh 1967: p. 396).

GPS-tracking schedules can be adjusted to overcome this problem by consulting and following general suggestions for monitoring forest resources (de Gruijter et al. 2006), and more specifically for macrofungi (Lodge et al. 2004). Statistical procedures for analyzing spatio-temporal datasets such as those resulting from GPS-tracking mushroom gatherers, are thoroughly illustrated by Cressie and Wikle (2011). Additionally, agglomerative nesting algorithms (Kaufman and Rousseeuw 2008) can be used to compare the similarity of sites. In the latter case, for example, fungal frequency and abundance estimates (see Online Resource 1, Tables S1 and S2) could be used to group sites according to their similarity.

A TEK-based monitoring proposal

To establish a consistent TEK-based monitoring strategy we suggest that researchers and locals work on the following issues.

Identifying the "experts" and the "curious"

As soon as a mycophilic community has been contacted and their desire to participate in a study established, researchers should start identifying at least two types of people: (i) the mushroom "experts", and (ii) the "curious" in relation to GPS-tracking and handling data. In their original essay Davis and Wagner (2003) encourage researchers to use a systematic methodological approach to identify experts. In the case of wild edible fungi, identifying who holds the largest body of TEK within a community can certainly be helpful in interpreting and comparing estimated fungal diversity from the data of GPS-tracked trips. However, the application of TEK need not be limited to a few individuals and anyone able to GPS-track their own or others' trajectories can provide real-time information. For this reason, it is also essential to identify who is curious about GPS-tracking trajectories and who is not.

Ethnographic research must complement GPS-tracking. The techniques to document TEK and describe how widespread it is within a community can vary as different researches show (Anadon et al. 2009; Crona and Bodin 2006; He et al. 2009; LaRiviere and Crawford 2013). It was Davis and Wagner (2003) who initially presented a useful protocol for achieving this. Among the key factors they list for accurately documenting TEK are: exploratory interviews, asking who is considered an expert, ranking people mentioned by informants, interviewing mentioned people, contacting as many people as possible to obtain a representative sample, agreement by at least three people on environmental ecological features culturally described, identifying the number of generations through which TEK has been transmitted, and proper instrumental design. The principal methods for documenting TEK have been interviews (open-ended, close-ended, semi-directive, formal and informal), although participant observation and analytical workshops are also useful and desirable (Brook and McLachlan 2008; Fraser et al. 2006; Uprety et al. 2012).

By adopting this approach and these methods, researchers and community members are enabled to document TEK about wild edible mushrooms': (i) taxonomy, (ii) distribution, (iii) phenology, (iv) fruiting patterns and related environmental factors, (v) management and conservation practices, (vi) ways of cooking, or (vii) folktales. This information could be complemented and compared later with information obtained from GPS-tracked pathways and community owned or nearby weather stations. After prolonged stays or regular visits to the community, researchers would be able to suitably design structured instruments for learning more about gatherers' system of knowledge in relation to edible mushrooms and the forest.

GPS-tracking operation

Participant observation should be conducted so gatherers can witness how their pathways can be GPS- and audio-tracked (Pacheco-Cobos et al. 2009). During this phase researchers need to: (i) document the traditional names of fungi and sites at which these are collected, (ii) obtain voucher specimens and photographs according to established protocols (Lodge et al. 2004), and (iii) prepare illustrated guides containing scientific and traditional names and their synonyms. By working together with mushroom gatherers on the latter, a general consensus on how species will be referred to can be reached. The resulting catalogues must be accessible to all in the community. In a second phase, the curious or interested locals should be encouraged to join a training workshop for tracking pathways, audio recording collection events, filling recording sheets, and handling spatio-temporal data. Repeated gathering trips with interested locals under training will help to: (i) prepare them to solve GPS-tracking or audio-recording technical problems in the field, and (ii) obtain paired recordings that can be compared for inter-observer reliability.

When remaining in the field for long periods is not possible, researchers should arrange periodic visits to the community to conduct planned ethnographic research or to collect logged data in GPS and voice recording units. As a recommendation, GPS units should be set to track participants' pathways with a standard rate that provides sufficient resolution (i.e. no less than 30 s per log), and also according to the number and duration of trips to be made.

A tracking schedule should be arranged in advance (e.g. every two weeks to yearly) and be approved by the community's authorities and members; turns for each family can be systematically or randomly assigned. When scheduling the people to be tracked, researchers should take into account potential differences between men and women in mushroom gathering (Pacheco-Cobos et al. 2010). Trackers will need to associate every waypoint number with the amount of sporocarps and traditional name of the gathered species, by recording these in a voice recorder. The start and finish times of all trips should be recorded either as waypoints or as time of the day in a voice recorder. Trackers would also need to fill pre-designed recording sheets to specify dates, sites visited, search party composition, and the amount (kg) of fungi obtained for each species. Other details regarding their foraging decisions could be obtained through interviews.

Length and terms of collaboration

Monitoring efforts should be conducted for a minimum of two to three years. During the first year curious mushroom gatherers can learn to track their own or others' pathways, and also to process the biological and geographical information that constitutes part of their knowledge system. To encourage gatherers to learn how to operate GPS devices and to rigorously register the collections they make, a monetary return for every tracked trip should be convened. A work-day, according to each country's instrument-operator's wage standard, should be used as the basal amount to be paid. Researchers must make explicit to gatherers, during communal meetings and organized workshops, the type of information a GPS-tracked pathway should contain in order to obtain a monetary compensation.

Researchers will provide the community with all equipment necessary to systematically GPS-track pathways. The basic kit must include: a GPS unit, voice recorder, recording sheets, office supplies, batteries, solar panel (if no power supply available), small bags for carrying equipment, hand scales, bags for specimens and dry bags to protect equipment. If possible, mounting a weather station in the community would be desirable. Otherwise, the nearest weather stations should be identified and the access to climate records guaranteed. Laptop or desk computers should be available at arranged times for downloading and processing data.

Automated downloading and preprocessing of the data can be arranged by researchers, and workshops can be setup to instruct the community on how these procedures work, where curious trackers and researchers could work together in cleaning GPX files of errors and transcribing audio files into readable spreadsheets. Descriptive analysis of data should be performed by the end of the season (yearly), and shared with families or the whole community. How information will be shared, within and outside the community should be discussed in advance in order to protect families' secret collection sites and the community's forest resources (Gilmore and Eshbaugh 2011). The levels at which this information can be shared are: (i) family, (ii) community, or (iii) academic. For all of these needs an Internet portal could be built.

The correct execution of this researcher-community interaction must be based on a code of ethics, trust and commitment. The benefits of monitoring forest resources, edible fungi in this case, should be clear to all participants at all times. Among the short-term benefits we can mention are: remunerated monitoring, and organization of workshops to learn how to cultivate mushrooms (e.g. *Pleurotus* spp. or *Lentinula edodes*) in the dry season. Other community interests could be discussed in order to establish to what extent researchers can help. Long-term benefits resulting from the appropriate management of fungi, if not already recognized by the community, might not be easy to explain or present as a rationale or stimulus for monitoring efforts. However, it should be indicated that monitoring would allow everyone to learn about the availability and production of fungi in relation to different environmental and anthropogenic variables (e.g. temperature, rainfall, soil, land use, gathering intensity). In this sense we could gain information about the features of the forest's productive cycles. The researchers and the community members should be aware of further funding opportunities that trained trackers' families could obtain in exchange for the large amount of valuable ecological information on edible fungi they could provide by GPS-tracking.

By actively involving community members in different research phases, organizing senior and co-authorships, and exploring possible economic partnerships with industries, scientists could ensure that local knowledge holders will continue participating in ecological research and co-management aimed at conservation (Brook and McLachlan 2008; Cheveau et al. 2008). With respect to mushrooms, Garibay-Orijel et al. (2009) developed an inclusive model to integrate these into sustainable management for the community's indigenous forest.

Given the large returns, estimated in USD millions, that wild edible fungi (e.g. *Tricholoma* spp., *Morchella* spp., *Boletus* spp. or *Cantharellus cibarius*) can bring on the international market (Boa 2004), exploring means to preserve (dry), pack, and transport wild mushrooms would be appropriate to develop a commercialization strategy. The work of He et al. (2009) is a good example on how participatory technology development can be conducted. Furthermore, by integrating different disciplines and TEK investigations He et al. (2011) learned how ecological and social factors affect *Thelephora ganbajun* availability and proposed an integrative management strategy to commercialize it.

Perspectives

Committed and collaborative work will permit the implementation of a TEK-based monitoring strategy, as proposed here. The tracking method described by Pacheco-Cobos et al. (2009), complemented with rigorous TEK research in mycophilic cultures, can provide scientists and participating communities with data for: (i) testing hypotheses on Human behavioral ecology (HBE) in natural settings, (ii) reliably describing spatio-temporal patterns of fungal availability in relation to cultural or environmental factors, (iii) making cross-cultural comparisons of the use of edible fungi, and (iv) developing consistent conservation programs based on ecological evidence and community interests.

Nettle et al. (2013) have recognized that HBE research would benefit from studies dealing with navigation, resource extraction, spatial patterns of habitat use, social coordination, among other topics. Our proposal provides a practical means to do so, since high-resolution records in space and time can be obtained. Researchers could systematically designate which mushroom gatherers are to be GPS-tracked and/or schedule gathering mushroom trips to established sites, depending on the conditions they would like to test or learn from. Cross-cultural comparisons, particularly in areas shared by two or more cultures, would be worth conducting since the diversity of the edible fungi used can vary according to cultural preferences (Montoya et al. 2002).

Given that the fruiting patterns of edible fungi are not fully understood, it is important to use TEK to study their ecology and spatio-temporal distribution. In this sense, recording the locations at which gatherers know a species' mycelia are present (based on previous collections), even when no sporocarps are detectable, can certainly help monitoring such species' availability in the wild. Encounter types (*memory*, *traces*, *failed collection*, and *exploration*), even when not resulting in successful collections, reflect gatherers' ecological knowledge of fungi. Thus, systematically recording these encounter types can also provide useful information for describing fungal diversity. Further spatial or temporal analyses could be conducted to learn, based on distances to nearest neighbors, how many times each sampled location (pair of geographical coordinates for collection events) has been visited through one or several rainy seasons.

Ethnobiological work in future years, with greater participation of indigenous researchers, might help in explaining and strengthening the link between TEK and the collective custody of biological diversity (De Ávila 2008). Educational opportunities for interested or talented locals and ecosystem management incentives for the community should be anticipated and encouraged; in this sense institutional facilities and networks close to field sites can provide good starting points, and also serve as "bridging organizations" for building trust and power relations and resolving conflict (Folke et al. 2005). We propose to combine participatory research (design, monitoring, analysis) with local systems of knowledge in order to provide TEK owners with alternative tools and criteria for adaptively managing their environment.

Conclusions

- We have illustrated how information from GPS-tracked pathways can be used to describe the diversity and distribution of edible fungi, and how foragers' TEK can be used as an alternative to monitor and manage this important resource.
- We recommend:
  - Further study of cultural preferences in relation to fungal frequency and abundance, to learn if gatherers' collection frequency is positively correlated with mushroom fruiting patterns.

  - Adjusting the GPS-tracking schedules to obtain balanced samples, a requirement for statistical comparisons of fungal diversity and distribution between sites and dates.

- We have presented an outline for implementing a TEK-based monitoring scheme of wild edible fungi, which combines a GPS-tracking method with thoughtful interaction with communities in order to document TEK and co-plan research.

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